

AD-A048 058

CIVIL ENGINEERING LAB (NAVY) PORT HUENEME CALIF  
EXPANSIVE CEMENT CONCRETES FOR NAVAL CONSTRUCTION.(U)

F/G 11/2

UNCLASSIFIED

NOV 77 J R KEETON  
CEL-TN-1504

NL

|  $\sigma_f$  |

ADA048 058



AD A 048058

# Technical



TN no. N-1504

# Note

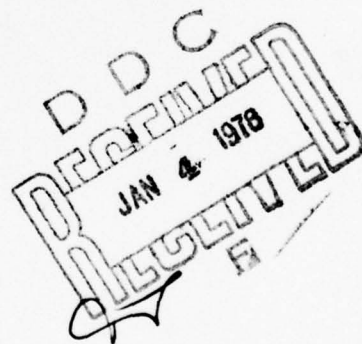
**title:** EXPANSIVE CEMENT CONCRETES  
FOR NAVAL CONSTRUCTION

**author:** John R. Keeton, P.E.

**date:** November 1977

**sponsor:** Director of Navy Laboratories

**program nos:** ZR000-01-137



AD No. \_\_\_\_\_  
DDC FILE COPY



## CIVIL ENGINEERING LABORATORY

NAVAL CONSTRUCTION BATTALION CENTER  
Port Hueneme, California 93043

Approved for public release; distribution unlimited.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER <b>14 CEL-TN-1504</b>	2. GOVT ACCESSION NO. DN244015	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) <b>EXPANSIVE CEMENT CONCRETES FOR NAVAL CONSTRUCTION</b>	5. TYPE OF REPORT & PERIOD COVERED <b>Final Rept. Jul 71 - Jun 75</b>	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) <b>John R. Keeton P.E.</b>	8. CONTRACT OR GRANT NUMBER(s)	
9. PERFORMING ORGANIZATION NAME AND ADDRESS <b>CIVIL ENGINEERING LABORATORY Naval Construction Battalion Center Port Hueneme, California 93043</b>	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61152N <b>16 ZR00001137</b>	<b>17 ZR00001137</b>
11. CONTROLLING OFFICE NAME AND ADDRESS <b>Director of Navy Laboratories Department of the Navy Washington, DC 20360</b>	12. REPORT DATE <b>Nov 77</b>	13. NUMBER OF PAGES <b>89p.</b>
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (if different from this page) Unclassified	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)  Expansive concrete, shrinkage-compensating concrete, expansion, shrinkage, steel reinforcement, expansive cement.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  Expansion and subsequent shrinkage characteristics of shrinkage-compensating concrete were determined in mesh-reinforced prisms. The prisms were cured in fog for 14 days and then subjected to drying in either 25%, 50%, or 75% relative humidity (all at 73F). The concretes were made with four different aggregate types: (1) moderate quality river aggregate, (2) moderate quality limestone aggregate, (3) light-weight coarse aggregate and river sand, and (4) lightweight coarse and fine aggregates. Maximum		

DDC  
RECEIVED  
JAN 4 1978  
E

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

continued

Unclassified  
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

391111

*James*

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

20. Continued

aggregate size was 3/8 inch. The effects of the following variables on expansion and shrinkage were determined: amount of cement, amount of reinforcement, prism thickness, and relative humidity of shrinkage environment. Design recommendations are made for use of shrinkage-compensating expansive concretes in various climatic areas.

Library Card

Civil Engineering Laboratory  
EXPANSIVE CEMENT CONCRETES FOR NAVAL  
CONSTRUCTION (Final), by John R. Keeton, P.E.  
TN-1504 91 pp illus November 1977 Unclassified

1. Shrinkage-compensating concrete 2. Expansive concrete 1. ZR000-01-137

Expansion and subsequent shrinkage characteristics of shrinkage-compensating concrete were determined in mesh-reinforced prisms. The prisms were cured in fog for 14 days and then subjected to drying in either 25%, 50%, or 75% relative humidity (all at 73F). The concretes were made with four different aggregate types: (1) moderate quality river aggregate, (2) moderate quality limestone aggregate, (3) light-weight coarse aggregate and river sand, and (4) lightweight coarse and fine aggregates. Maximum aggregate size was 3/8 inch. The effects of the following variables on expansion and shrinkage were determined: amount of cement, amount of reinforcement, prism thickness, and relative humidity of shrinkage environment. Design recommendations are made for use of shrinkage-compensating expansive concretes in various climatic areas.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Blank



## Table of Contents

	Page
BACKGROUND . . . . .	1
INTRODUCTION . . . . .	1
FACTORS AFFECTING EXPANSION OF CEMENTS . . . . .	3
Chemical Composition and Fineness . . . . .	3
Amount of Expansive Material. . . . .	3
Water/Cement Ratio (W/C). . . . .	3
Curing. . . . .	4
Size and Shape of Member. . . . .	4
Restraint . . . . .	4
Mixing Time . . . . .	5
Use of Admixtures . . . . .	5
Type and Size of Aggregate. . . . .	5
Age of Expansive Cement . . . . .	6
PROPERTIES OF SHRINKAGE-COMPENSATING EXPANSIVE CEMENT CONCRETES. .	6
RESEARCH PROGRAM . . . . .	7
Test Specimens. . . . .	7
Aggregate . . . . .	8
Expansive Cement Concrete Mixes . . . . .	8
Concrete Mixing Procedure . . . . .	9
Curing and Storage to Test Specimens. . . . .	9
Length Change Measurements. . . . .	9
Theoretical Consideration . . . . .	10
TEST RESULTS . . . . .	11

1715
White Section ☒

1716
Blue Section ☐

1717
☐

1718
1719

1720
1721

1722
1723

1724
1725

1726
1727

1728
1729

1730
1731

1732
1733

1734
1735

1736
1737

1738
1739

1740
1741

1742
1743

1744
1745

1746
1747

1748
1749

1750
1751

1752
1753

1754
1755

1756
1757

1758
1759

1760
1761

1762
1763

1764
1765

1766
1767

1768
1769

1770
1771

1772
1773

1774
1775

1776
1777

1778
1779

1780
1781

1782
1783

1784
1785

1786
1787

1788
1789

1790
1791

1792
1793

1794
1795

1796
1797

1798
1799

1800
1801

1802
1803

1804
1805

1806
1807

1808
1809

1810
1811

1812
1813

1814
1815

1816
1817

1818
1819

1820
1821

1822
1823

1824
1825

1826
1827

1828
1829

1830
1831

1832
1833

1834
1835

1836
1837

1838
1839

1840
1841

1842
1843

1844
1845

1846
1847

1848
1849

1850
1851

1852
1853

1854
1855

1856
1857

1858
1859

1860
1861

1862
1863

1864
1865

1866
1867

1868
1869

1870
1871

1872
1873

1874
1875

1876
1877

1878
1879

1880
1881

1882
1883

1884
1885

1886
1887

1888
1889

1890
1891

1892
1893

1894
1895

1896
1897

1898
1899

1900
1901

1902
1903

1904
1905

1906
1907

1908
1909

1910
1911

1912
1913

1914
1915

1916
1917

1918
1919

1920
1921

1922
1923

1924
1925

1926
1927

1928
1929

1930
1931

1932
1933

1934
1935

1936
1937

1938
1939

1940
1941

1942
1943

1944
1945

1946
1947

1948
1949

1950
1951

1952
1953

1954
1955

1956
1957

1958
1959

1960
1961

1962
1963

1964
1965

1966
1967

1968
1969

1970
1971

1972
1973

1974
1975

1976
1977

1978
1979

1980
1981

1982
1983

1984
1985

1986
1987

1988
1989

1990
1991

1992
1993

1994
1995

1996
1997

1998
1999

2000
2001

2002
2003

2004
2005

2006
2007

2008
2009

2010
2011

2012
2013

2014
2015

2016
2017

2018
2019

2020
2021

2022
2023

2024
2025

2026
2027

2028
2029

2030
2031

2032
2033

2034
2035

2036
2037

2038
2039

2040
2041

2042
2043

2044
2045

2046
2047

2048
2049

2050
2051

2052
2053

2054
2055

2056
2057

2058
2059

2060
2061

2062
2063

2064
2065

2066
2067

2068
2069

2070
2071

2072
2073

2074
2075

2076
2077

2078
2079

2080
2081

2082
2083

2084
2085

2086
2087

2088
2089

2090
2091

2092
2093

2094
2095

2096
2097

2098
2099

2100
2101

2102
2103

2104
2105

2106
2107

2108
2109

2110
2111

2112
2113

2114
2115

2116
2117

2118
2119

2120
2121

2122
2123

2124
2125

2126
2127

2128
2129

2130
2131

2132
2133

2134
2135

2136
2137

2138
2139

2140
2141

2142
2143

2144
2145

2146
2147

2148
2149

2150
2151

2152
2153

2154
2155

2156
2157

2158
2159

2160
2161

2162
2163

2164
2165

2166
2167

2168
2169

2170
2171

2172
2173

2174
2175

2176
2177

2178
2179

2180
2181

2182
2183

2184
2185

2186
2187

2188
2189

2190
2191

2192
2193

2194
2195

2196
2197

2198
2199

2200
2201

2202
2203

2204
2205

2206
2207

2208
2209

2210
2211

2212
2213

2214
2215

2216
2217

2218
2219

2220
2221

2222
2223

2224
2225

2226
2227

2228
2229

2230
2231

2232
2233

2234
2235

2236
2237

2238
2239

2240
2241

2242
2243

2244
2245

2246
2247

2248
2249

2250
2251

2252
2253

2254
2255

2256
2257

2258
2259

2260
2261

2262
2263

2264
2265

2266
2267

2268
2269

2270
2271

2272
2273

2274
2275

2276
2277

2278
2279

2280
2281

2282
2283

2284
2285

2286
2287

2288
2289

2290
2291

2292
2293

2294
2295

2296
2297

2298
2299

2300
2301

## TABLE OF CONTENTS (Cont'd)

	Page
Expansion Strains During The Curing Period . . . . .	11
Expansion-Shrinkage of 7.5 SC Prisms . . . . .	12
Expansion-Shrinkage of 7.5 SCA Prisms. . . . .	13
Expansion-Shrinkage of 7.5 SC-L and 7.5 SCA-L. . . . .	13
Expansion-Shrinkage of 7.5 SCA-SLW Prisms. . . . .	14
Expansion-Shrinkage of 7.5 SCA-LW Prisms . . . . .	15
SC Mixes With Different Cement Contents. . . . .	15
Compressive Strengths and Young's Moduli . . . . .	16
DESIGN APPLICATIONS . . . . .	16
Design Examples. . . . .	17
CONCLUSIONS . . . . .	19
RECOMMENDATIONS . . . . .	19
ACKNOWLEDGEMENTS. . . . .	19
REFERENCES. . . . .	19

## BACKGROUND

The industrial manufacture of portland cement involves pulverizing raw materials containing lime, silica, alumina, and iron oxide, [1,2] (properly proportioned) to obtain the desired chemical composition. The ingredients are then heated at 2,600F (1,427C) to 3,000F (1,649C) to form portland cement clinker, which is later pulverized to form portland cement. The products formed are tricalcium silicates ( $C_3S$ ), dicalcium silicates ( $C_2S$ ), tricalcium aluminate ( $C_3A$ ), and tetracalcium aluminoferrite ( $C_4AF$ ). The setting of  $C_3S$  and  $C_2S$  is fairly slow, but setting of  $C_3A$  is very rapid. Not much  $C_3A$  is found in modern portland cements, but the finer nature of these cements makes flash setting of  $C_3A$  more probable. It was found, however, that addition of small amounts of gypsum prevents flash setting of  $C_3A$ . For this reason, very carefully controlled amounts ( $\pm 0.10\%$ ) of gypsum are added to the cement during the final pulverizing step. The gypsum ( $CaSO_4 \cdot 2H_2O$ ) combines with the  $C_3A$  to form a needle-like insoluble compound called calcium sulfoaluminate ( $C_6AS_3 \cdot 32H_2O$ ). This product, called ettringite because it resembles the natural mineral ettringite, occupies a fairly large volume; too much of it could result in damaging expansions after the cement has hardened. Under normal conditions the small amount of ettringite formed by the addition of a slight amount of gypsum to prevent flash setting does not result in damaging expansions. However, the recognition of the potential expansions resulting from formation of ettringite led to development of expansive cements as we now know them.

This technical note is the final report on a research study at the Civil Engineering Laboratory (CEL) directed toward use of expansive cement concretes in thin-shell and conventional construction at Navy shore bases.

## INTRODUCTION

The development of expansive cements has been documented by several authors [3,4,5] and by Technical Committee 223 of the American Concrete Institute (ACI). [6,7] The following remarks regarding this development were taken from these references.

The motivating stimulus behind development of expansive cements was twofold: (1) elimination of shrinkage cracking and (2) inducement of relatively high levels of precompression in the concrete, much as is done by mechanical prestressing. The twofold objective resulted in development of (1) a shrinkage-compensating expansive cement and (2) a self-stressing expansive cement. The principal difference between the two classes of expansive cements is the amount of expansive component



provided for reaction with portland cement ingredients to form ettringite, the expansion producer.

Purposeful research and development on the use of ettringite to produce expansions intended to overcome the effects of shrinkage and to self-stress concrete began in France in the mid-1930's. An expansive cement for repairs and for waterproofing as well as for self-stressing was developed in Russia. Studies by Klein, et al, at the University of California (Berkeley) led to the development of commercial expansive cements.[3,4]

ACI Committee 223 lists the following definitions pertinent to expansive cements and concretes:[6,7]

1. Expansive cement - A cement which when mixed with water forms a paste that, after setting, tends to increase in volume to a significantly greater degree than portland cement paste; used to compensate for volume decrease due to shrinkage or to induce tensile stress in reinforcement (post-tensioning).
2. Expansive cement Type K - A mixture of portland cement, anhydrous tetracalcium trialuminate sulfate ( $C_4A_3\bar{S}$ ), calcium sulfate ( $CaSO_4$ ) and lime ( $CaO$ ). The  $C_4A_3\bar{S}$  is a constituent of a separately burned clinker that is interground with portland cement; or, alternately, it may be formed simultaneously with the portland cement clinker compounds during the burning process.
3. Expansive cement Type M - Interground or blended mixtures of portland cement, calcium aluminate cement, and calcium sulfate suitably proportioned.
4. Expansive cement Type S - A type of portland cement containing a large computed  $C_3A$  content and interground with an amount of calcium sulfate above the usual amount found in portland cement.
5. Expansive cement concrete - a concrete made with Type K, Type M, or Type S expansive cement.
6. Shrinkage-compensating concrete - An expansive cement concrete which when properly restrained by reinforcement or other means will expand an amount equal to or slightly greater than the anticipated drying shrinkage. Because of the restraint, compressive stresses will be induced in the concrete during expansion. Subsequent drying shrinkage will reduce these stresses; but, ideally, a residual compression will remain in the concrete, thereby eliminating shrinkage cracking.
7. Self-stressing concrete - An expansive cement concrete in which expansion, if restrained, induces compressive stresses of a high enough magnitude to result in significant compression in the concrete after drying shrinkage has occurred. The level of precompression in self-stressing concrete is in the range of 300 to 1,000 psi (21 to 70.3 kg/cm<sup>2</sup>).
8. Ettringite - The phase formed during the hydration of expansive cements; it is the source of the expansive force. It is comparable to the natural mineral of the same name.



## FACTORS AFFECTING EXPANSION OF CEMENTS

Purposeful expansion is one of the features distinguishing expansive cements from portland cements. As shown by other researchers, the amount of achievable expansion for a given cement is dependent upon the factors listed below.

### Chemical Composition and Fineness

Rate of expansion is proportional to the amount of readily hydratable aluminates so long as  $\text{CaSO}_4$  is available.[6] The aluminates may be  $\text{C}_4\text{A}_3\text{S}$  (Type K), calcium aluminate cement (Type M), or  $\text{C}_3\text{A}$  (Type S). As the fineness of an expansive cement increases, the amount of expansion decreases. The increase in fineness accelerates the formation of ettringite. If the bulk of expansion takes place before the concrete has achieved sufficient strength, it will be wasted; on the other hand, if the bulk of the expansion occurs after the concrete has reached a relatively high strength level, internal damage may result from the expansions. A Blaine fineness of about 2800 seems optimum.[8]

### Amount of Expansive Material

Generally speaking, the more expansive material present, the more will be the expansion. The essential expansion ingredients can be proportioned into all types of expansive cements to cover the entire range of expansions. The commercially available Type K shrinkage-compensating cements are proportioned to produce relatively low expansions. The Type K cements contain from 10% to 15% expansive components having from 25% to 50% calculated  $\text{C}_4\text{A}_3\text{S}$  (calcium sulfoaluminate). Laboratory studies on Type K self-stressing cements have utilized contents of expansive component from 10% to 50%. Expansion of self-stressing cements is related to amount of expansive component but not proportionately. Polivka and Bertero [9] have recommended that the influence of amount of expansive component in self-stressing cements be evaluated in the specific type of concrete to be used.

### Water/Cement Ratio (W/C)

Generally speaking, it has been found that the lower the W/C, the higher the expansion; however, changes in W/C also affect relative proportions of other ingredients.[6] For instance, concretes with the same cement content can be made with a range of values of W/C. In this case, all the concretes would have the same potential for expansion (cement content); but the more pervious, higher slump concretes (higher W/C) will take up curing water more readily and therefore will expand somewhat more (see below on effects of curing on expansion).

## Curing

The requirements for proper curing of expansive cement concretes are more stringent than for portland cement concrete. [6,7] The formation of the strength-producing calcium silicate hydrates ( $C_3S$  and  $C_2S$ ) and the expansion-producing ettringite are affected differently by curing temperature and by availability of water. Inadequate curing can substantially reduce the level of expansion. All expansive cement concretes expand significantly more when cured under water or in a moist room than they do when cured in an environment in which water is not available to the concrete. Curing under a polyethylene sheet greatly reduces expansions when compared to water curing. Steam-cured expansive concretes expand only about 80% as much as when water-cured. Lightweight concretes, in which the highly absorptive lightweight aggregates give off water and thus provide a form of internal curing, have been shown to have higher expansion characteristics than concrete made with normal weight aggregates, especially in larger sections where a moisture gradient is usually established.[10] The presence of internal water also reduces the potentially damaging effects of differential expansions in the larger sections. Results of tests to determine the effects of curing temperature on expansion are conflicting. More research is needed.

## Size and Shape of Member

Other things being equal, expansion decreases as the size of the member increases. In addition, the exterior can expand at a different rate from the interior of large moist-cured members and when these differences are significant, mechanical properties are adversely affected.[6] As stated above, internal curing achieved by using lightweight aggregate tends to alleviate these differentials. The influence of shape of member has not yet been determined.

## Restraint

Successful utilization of any of the expansive cement concretes depends upon the amount and type of resistance to the expansion of the concrete. An expansive cement concrete in which no resistance is provided to the expansion shows greatly reduced mechanical properties. In the language of the expansive cement industry the resistance to expansion is called "restraint." Restraint can be either external, as in the case of rigid framework, or internal in the form of reinforcing steel or mesh.[5,6,7,11] Some degree of restraint can also be provided by such forces as subgrade friction and by abutting structures. In the case of reinforcing steel or mesh, the developing bond strength provides the necessary restraint to expansion. Resistance to the expansion places the steel in tension; this, in turn, places

the concrete in compression, much as in prestressed concrete. Most tests have been made on specimens using uniaxial (longitudinal) restraint. Generally speaking, it has been found that the more the restraint (percent of reinforcement) the less the measured expansion and the more the induced compression in the concrete. However, since the expansion potential for a given concrete is the same regardless of degree of restraint, an increase in longitudinal restraint (uniaxial) might cause lateral expansions large enough to adversely affect the mechanical properties.[11] For this reason, there is an optimum amount of uniaxial restraint for a given expansive cement concrete that will produce adequate prestress forces, minimum lateral expansions, and best mechanical properties. Most field installations of shrinkage-compensating concretes have utilized successfully the amount, kind, and position of reinforcement required for the given structure. Some tests made with biaxial restraint have shown improvements in uniformity of expansion and in mechanical properties. Due to their higher level of expansion, self-stressing concretes may require triaxial restraint, although successful tests have been made with biaxial restraint.

#### Mixing Time

Increasing mixing time decreases the expansion of a given expansive cement concrete.[6] Mixing accelerates formation of ettringite and thus depletes its availability for later expansion. Continued mixing also increases the water required to obtain a given slump.[7]

#### Use of Admixtures

Air-entraining admixtures which comply with ASTM C260 may be used for the same purpose with shrinkage-compensating concretes as with other types of portland cement concrete.[7] Some ASTM C494 Types A, B, and D water-reducing, retarding, and water-reducing/retarding admixtures are not compatible with certain shrinkage-compensating cements. It is recommended that such admixtures be tested before acceptance, using the particular cement and other materials selected for the job.[7] Calcium chloride (accelerator) is generally not recommended for use in expansive cement concrete because it reduces expansion and increases subsequent drying shrinkage.

#### Type and Size of Aggregate

Both rate and amount of expansion are affected by type of aggregate.[6,10] Of three types tested (crushed granite, river gravel, and expanded shale), the expanded shale concrete expanded the most and the river gravel the least. Data on the effects of aggregate size are limited. For a given workability, yield, and W/C, an increase in aggregate size is accompanied by a decrease in cement content. This change in cement content may cause a greater change in expansion than would the change in aggregate size.



## Age of Expansive Cement

The length of storage of expansive cement after manufacture tends to reduce slightly the restrained expansion. The best practice is to keep the cement in sealed drums, away from exposure to air.[6]

## PROPERTIES OF SHRINKAGE-COMPENSATING EXPANSIVE CEMENT CONCRETES

The following statements regarding properties of expansive cement concretes are based on previous research data obtained by other researchers together with observations made during and after field installations of full-size structures.[5,6,7,12,13]

1. Workability.[6] The workability of concretes made with Type K, Type S, and Type M shrinkage-compensating cements is the same as for portland cement concrete of equal slump. Type K cement seems to require slightly more water for the same slump, but the additional water probably combines with the expansive component and thus does not appear to adversely affect the other properties (W/C, strength, etc.).

2. Bleeding.[6] All three expansive cements have shown a consistent decrease in bleeding compared with similar portland cement concretes. In some cases there has been no bleeding at all with expansive cement concretes.

3. Setting time.[6] Setting times of all three shrinkage-compensating cements are comparable to Type I portland cement.

4. Unit weight and yield.[6] Shrinkage-compensating concretes have about the same unit weight and yield as does portland cement concrete (other things being equal).

5. Strengths.[6,7,12] Shrinkage-compensating concretes develop compressive, tensile, and flexural strengths equivalent in rate and magnitude to concretes made with Type I and Type II portland cements.

6. Modulus of elasticity (E).[6,7] Moduli of elasticity - static and dynamic - of shrinkage-compensating concretes are comparable to those in portland cement concretes.

7. Shrinkage and creep.[6,7] Shrinkage and creep of shrinkage-compensating concrete is about the same as in portland cement concrete.

8. Bond Strength.[6] Very few comparative bond strength tests have been made. Those tests which have been made showed that bond strengths of concrete made with Type K shrinkage-compensating cement were equal to or greater than those in the companion portland cement concrete.

9. Coefficient of thermal expansion.[6] The few tests which have been made show a coefficient similar to portland cement concrete.



10. Resistance to freezing and thawing.[13] Shrinkage-compensating concretes can be made resistant to damage from freezing and thawing with proper air entrainment and with relatively high cement content.

11. Resistance to de-icer scaling.[12,13] Shrinkage-compensating concretes showed resistance to de-icer scaling equal to or greater than comparable portland cement concrete.

12. Resistance to sulfate attack.[6,12] Very few tests have been conducted. Results are contradictory, with some showing favorable resistance of shrinkage-compensating concretes to sulfate attack and some unfavorable.

13. Abrasion resistance.[6] Shrinkage-compensating concrete made with Type K cement was found to have abrasion resistance superior to that of portland cement concrete.

#### RESEARCH PROGRAM

The research program at CEL was designed to determine the efficacy of using expansive cement concretes for Naval construction of thin-shell structures. Listed below are the major factors which were investigated:

1. Amounts of expansion to be expected with different cement contents
2. Effects of different amounts of restraint on expansion
3. Expansion of test specimens of different sizes
4. Shrinkage effects in different drying environments
5. Effects of air-entrainment on expansion
6. Effects of type and weight of aggregate on expansion

A detailed listing of the research program involving the expansive cement concrete prisms is presented in Table 1.

#### Test Specimens

To simulate concrete thin shells, prismatic specimens 5 in. (12.7 cm) wide and 12 in. (30.5 cm) long were made in thicknesses of 1, 2, and 4 in. (2.5, 5.1, and 10.2 cm). Figure 1 shows one of each of these prism sizes. The edges of the prisms were sealed to water vapor, so that subsequent drying of the concrete occurred only from the 5- by 12-in. (12.7 by 30.5 cm) opposite faces. This was done to simulate a continuous thin-shell structure in which drying would be from the upper and lower surfaces. The first prisms were reinforced with galvanized welded wire fabric of the following spacing and wire sizes: 2 by 2 in. (5.1 by 5.1 cm) No. 14 and No. 12 and 1 by 1 in. (2.5 by 2.5 cm), No. 14 and

No. 12. Examples of placement of the fabric with respect to the forms is shown in Figures 2a, b, and c. To obtain lower steel percentages for the 1-in.-thick (2.5 cm) prisms, some of them were made in widths of 10 in. In these prisms, welded wire fabric 4 by 4 in. (10.2 by 10.2 cm) No. 14 was used. Several different percentages of reinforcement were obtainable, as indicated in Table 2. Computation of reinforcement percentage was based on the total cross-sectional area of the horizontal wires viewed from either end. The vertical wires completing the fabric were not considered in computing the steel-percentage. In this report, reinforcement is designated by a lower case p followed by a percentage, e.g.,  $p = 0.15\%$ .

Also visible in Figure 2 are the screws which served as reference points for measurement of length changes with a mechanical strain gage. The reference screws were 5 in. (12.17 cm) apart.

#### Aggregate

Concretes used in this study were made with: (1) a moderate quality river sand and gravel, (2) a moderate quality crushed limestone (coarse and fine), and (3) an expanded shale lightweight aggregate (coarse and fine). All aggregates were dried prior to use but were not screened into separate sizes.

#### Expansive Cement Concrete Mixes

The expansive cement used was the shrinkage-compensating Type K sold commercially as "ChemComp Cement." Mixes were made over a wide range of cement contents (590 to 1,034 lb/yd<sup>3</sup> - 350 to 613 kg/m<sup>3</sup>) and water/cement ratios (0.376 to 0.596 by weight), both with and without entrained air. For comparison, a few mixes were made with portland Type II cements. In this report the concrete mixes are designated by the number of equivalent bags per cubic yard followed by the type of cement used, e.g., 7.5 SCA means 7.5 bags/yd<sup>3</sup>, shrinkage-compensating cement, air entrained. The vast majority of the mixes of shrinkage-compensating concrete were made with 7.5 bags (705 lb) of cement per cubic yard because, at the time, this mix was typical of those being used in the Los Angeles area for structural purposes (other than slabs-on-grade).

The different types of shrinkage-compensating (SC) cement concretes used in this study are listed below.

1. 7.5 SC - normal weight river aggregate, non-air-entrained
2. 7.5 SCA - normal weight river aggregate, air-entrained
3. 7.5 SC-L - normal weight crushed limestone aggregate, non-air-entrained
4. 7.5 SCA-L - normal weight crushed limestone aggregate, air-entrained
5. 7.5 SCA-SLW - lightweight coarse aggregate and river sand, air-entrained (sand-lightweight)

6. 7.5 SCA-LW - lightweight coarse and lightweight fine aggregate, air-entrained (all-lightweight)

7. SC mixes - normal weight river aggregate, non-air-entrained  
6.3 SC, 7.5 SC, 8.25 SC, 9.1 SC, 10.25 SC, and 11.0 SC

#### Concrete Mixing Procedure

To simulate the average mixing and hauling time of truck mixers, the following mixing procedure was adopted:

1. Mix aggregate, cement, and  $3/4$  of water for 3 min
2. Stop the mixer for 5 min (total time 8 min)
3. Mix for 2 min (total time 10 min)
4. Stop the mixer for 5 min (total time 15 min)
5. Mix for 2 min (total time 17 min)
6. Stop the mixer for 5 minutes (total time 22 min)
7. Mix for 2 min (total time 24 min)
8. Stop the mixer for 5 min (total time 29 min)
9. Add the remaining mixing water
10. Mix for 2 min (total time 31 min)
11. Measure the slump, seeking 4 in. (10.2 cm), adjust if necessary and measure air content.
12. Cast the specimens, consolidating by vibration.

#### Curing and Storage of Test Specimens

The specimens were cured in 100% R.H. (fog) for 14 days prior to being placed in one of three controlled temperature and humidity environments (25% R.H., 50% R.H., or 75% R.H., all at 73F). The curing period of 14 days was found to be typical for job-curing in the Los Angeles area.

#### Length Change Measurements

All length change measurements on the test specimens began about 6 hours after casting, immediately after removal from the molds. The specimens were then placed in 100% R.H., and measurements of expansion during the curing period were made daily for 7 days and then at 14 days, at which time the specimens were transferred to one of the controlled rooms. Drying shrinkage in the controlled rooms was measured daily for 1 wk, weekly for 3 mo, then monthly for at least 1 yr. Expansion strains and subsequent shrinkage strains were obtained by dividing the



length change by the gage length of 5 in. (12.7 cm); strains are reported as microstrain ( $\mu$  in./in.) or as strain in percent, where 1% strain is equivalent to 10,000 microstrain.

#### Theoretical Consideration

As unreinforced and unstressed concrete dries, it shrinks (compresses), and no damage results from the shrinkage. However, if the shrinkage is resisted or restrained by reinforcement, tensile stresses of sufficient magnitude to cause the concrete to crack can be induced. These cracks, referred to as shrinkage cracks, are not only unsightly but often allow ingress of water and other particles, which can cause more severe damage. When the concrete portion of reinforced concrete is placed in compression prior to drying, the tensile stresses resulting from shrinkage must first overcome the compressive stresses already present before the concrete itself can crack due to tensile stress.

Shrinkage-compensating concrete expands during the curing period, and if this expansion is properly restrained (resisted), the steel reinforcing is stretched, placing the concrete to which it is bonded in compression. An ideal expansion-shrinkage curve is shown in Figure 3. The expansion during the curing period (origin to point A) is resisted by reinforcing, and the concrete is being compressed. As the concrete enters the drying period A to B (i.e., is placed in service), the concrete begins to shrink. This shrinkage is actually, in terms of strain, tensile in direction, but this tension must first overcome the "built-in" compression before the concrete undergoes a tensile stress; i.e., the strain curve as shown in Figure 3 from A to B must drop below the "zero" line to enter the tensile stress zone where the concrete might crack. For the conditions shown in Figure 3, the concrete, after shrinkage, is still in compression; therefore the concrete will not crack due to shrinkage stresses. The problem in designing a structure of shrinkage-compensating concrete, then, is that of providing the required restrained expansion to overcome the shrinkage the structure is expected to undergo. The amount of shrinkage to be expected in a given structure is principally dependent upon the localized environment and the thickness of the structure. Obtaining the required restrained expansion is dependent upon the interplay between shrinkage-compensating cement content, the percentage of reinforcing steel, and the thickness of the member. It should be emphasized that the concrete begins to "shrink" immediately after removal from fog curing, but the important aspect is whether or not-and to what extent-the shrinkage drops below the zero strain line into the zone of negative strain.



## TEST RESULTS

### Expansion Strains During the Curing Period

Expansion strains after 14 days of fog curing are shown in Tables 3, 4, and 5 for various mixes containing 7.5 bags of cement per cubic yard and for steel percentages of 0%, 0.15% and 0.30%. The only results in Tables 3, 4, and 5 which might have been considered predictable are the higher expansions found in the lightweight mixes (lines 5 and 6). If other things are equal, the longer the curing period (i.e., the longer the cement is exposed to liquid water), the higher is the expansion. It has been shown that some of the water absorbed by the highly porous lightweight aggregate during mixing later returns to the concrete matrix as the concrete dries, thus furnishing more water for continued hydration of cement.[14] The effects of air-entrainment upon expansion vary, in some cases showing lower expansion and in some cases higher expansion than non-air-entrained concrete. Expansion strains for  $p = 0\%$  should represent the "expansion potential" of a given mix and prism thickness.

Table 4 shows expansion strains for prisms 1 and 2 in. thick made with concretes containing various amounts of shrinkage-compensating cement. Since it is the cement that, in the end, provides the expansion, it then follows that the more the cement, the higher the expansion. This is corroborated in Table 4. The effects of cement content on expansion of prisms 1 inch thick are illustrated in Figure 4 for three steel percentages. Note that the left ordinate is shown in microstrain and the right ordinate in percent strain. As cement content increases from 6.3 bags/yd<sup>3</sup>, the rate of increase in expansion is rather high up to cement contents between 7.5 and 8 bags/yd<sup>3</sup>; then there is a decreasing rate of increase up to 11.0 bags/yd<sup>3</sup>.

Table 5 shows expansions of prisms with various steel percentages. As expected, expansion decreased as the resistance to the expansion increased. Figure 5 illustrates the effects of steel reinforcement on expansion of prisms 1 in. thick. With curves such as those shown in Figure 5, expansions at any amount of reinforcement between 0% and 0.78% is easily obtained. As indicated in Table 2, some of the welded wire fabric was 1 by 1 in. (2.5 by 2.5 cm), some 2 by 2 in. (5.1 by 5.1 cm), and some 4 by 4 in. (10.2 by 10.2 cm). Curves shown in Figure 5 reveal that this difference in spacing of wires does not affect the smoothness of the relationship between percent reinforcement and expansion.

A convenient means for determining the effects of specimen size upon certain properties of concrete is on the basis of the ratio of the exposed surface area to volume (S/V).[15,16] Exposed drying surfaces of the prisms were the 5 by 12-in. (10.2 by 30.5 cm) or 10 by 12-inch (25.4 by 30.5 cm) faces, the edge surfaces being sealed. Only the thickness affects the S/V, since widths and lengths cancel out. Figure 6 illustrates the relationship between 14-day expansion of 7.5 SC prisms and S/V for steel percentages from 0% to 0.78%. Expansions for intermediate thicknesses can be interpolated from the curves. As shown in

Figure 6, 14-day expansions decrease substantially as the specimen size increases. S/V values for thicknesses of 6 and 12 in., beyond the scope of this study, are also shown on Figure 6 along the lower right side. However, expansion for these thicknesses can be determined by extension of the curves to the origin of the graph as indicated by the dashed lines. An S/V value of zero would mean no specimen at all, and therefore the expansion would also be zero. S/V for a thickness of 3 ft is 0.67, and 6 ft is 0.33.

#### Expansion-Shrinkage of 7.5 SC Prisms

Residual strains of 1-in.-thick (2.5 cm) prisms after 365 days are presented as a function of steel percentage in Figure 7 and are also included in Table 6, along with corresponding values for 2- and 4-in.-thick (5.1 and 10.2 cm) prisms. Strain-time relationships are shown in Figures 8 a, b, and c for prisms 1 in. (2.5 cm) thick in 25% R.H., 50% R.H., and 75% R.H., respectively. Curves shown in Figure 8a for various steel percentages reveal that in 25% R.H. none of them approaches the ideal curve of Figure 3. Shrinkage rate of prisms 1 in. (2.5 cm) thick is extremely high in such a low humidity. The curve for 0% steel is included for general interest; as indicated previously, expansive cements are not recommended unless the concrete has some reinforcement, however slight. Data in Figure 8b for prisms 1 in. (2.5 cm) thick in 50% R.H. reveal that the curve for  $p = 0.15\%$  approaches the ideal in that it falls only slightly below the zero strain line after 1 year. In Figure 8c, data for 75% R.H., the curve for  $p = 0.15\%$  remains above the zero strain line, and the curve for  $p = 0.30\%$  falls only slightly below at 1 yr.

Relationships between residual strains after 365 days and relative humidity of drying environment are shown in Figure 9 for various steel percentages. For the conditions given i.e., for 7.5 SC concrete 1 in. (2.5 cm) thick, concrete with  $p = 0.15\%$  could be used in any exposure from 100% R.H. down to about 56% R.H. and remain above or at the zero strain line after 365 days. Likewise, concrete with  $p = 0.30\%$  could be used in any exposure from 100% R.H. to about 78% R.H.

Data interpolations shown in previous and subsequent tables and figures were obtained by harmonizing curvilinear relationships such as those shown in Figures 7 through 9.

Residual strains of 2-in.-thick (5.1 cm) prisms after 365 days are presented in Figure 10 and are also included in Table 6. Strain-time relationships are shown in Figures 11a and b for prisms 2 in. (5.1 cm) thick in 50% R.H. and 75% R.H., respectively. Figure 11a reveals that the curve for  $p = 0.15\%$  barely goes below the zero line at 1 yr. In 75% R.H., Figure 11b, the curve for  $p = 0.15\%$  stays well above the zero strain line, and the curve for  $p = 0.30\%$  barely drops below the zero strain line at 1 yr.

Relationships between residual strain after 365 days and relative humidity are shown in Figure 12. Study of these curves reveals that

7.5 SC concrete 2 in. (5.1 cm) thick could be used with  $p = 0.15\%$  from 100% R.H. to about 54% R.H. without dropping below the zero strain/line. Similarly, concrete with  $p = 0.30\%$  could be used from 100% R.H. to about 76% R.H.

Residual strains of 4-in.-thick (10.2 cm) prisms after 365 days are presented in Figure 13 and are also included in Table 6. Time-strain relationships are shown in Figure 14a and b for prisms 4-in. (10.2 cm) thick in 50% R.H. and 75% R.H. respectively. The curve for  $p = 0.15\%$  in Figure 14a, 50% R.H., remained above the zero strain line until 1 yr, at which time its residual strain value was zero. Curves for both  $p = 0.15\%$  and  $p = 0.30\%$  remained above the zero strain line in 75% R.H. (Figure 14b).

Relationships between residual strain and relative humidity are shown in Figure 15. These curves indicate that 7.5 SC concrete 4-in. (10.2 cm) thick could be used with  $p = 0.15\%$  from 100% R.H. to about 50% R.H. without dropping below zero residual strain. Similarly, concrete with  $p = 0.30\%$  could be used from 100% R.H. to about 73% R.H. without dropping below zero residual strain.

Residual strains after 365 days in 25% R.H., 50% R.H., and 75% R.H. are shown in Figure 16a, b, and c, respectively, as a function of S/V. The effects of member thickness is readily apparent in each of these figures. Use of Figures 16a, b, and c in conjunction with others, to establish design factors for given job conditions, is discussed later in this report.

#### Expansion-Shrinkage of 7.5 SCA Prisms

The 7.5 SCA concrete mix was identical to that of the 7.5 SC except for the air-entrainment and the necessary correction for mixing water; cement content was held constant at 7.5 bags per cubic yard. Prisms of 7.5 SCA concrete were made only in 1-in. (2.5 cm) thickness. Expansion strains after 14 days of fog curing are given in Table 3. Expansion for prisms with  $p = 0.15\%$  showed about 9% less expansion than the 7.5 SC prisms, but those prisms with  $p = 0.30\%$  showed about 2% more expansion than the 7.5 SC prisms.

Expansion-shrinkage curves for 1-in.-thick (2.5 cm) prisms of 7.5 SCA concrete in 75% R.H. are shown in Figure 17, along with corresponding curves for 7.5 SC concrete taken from Figure 8c. Effectively, there are no significant differences between the two concretes, meaning that after 1 yr, air entrainment has little or no effect on the net expansion-shrinkage performance.

#### Expansion-Shrinkage of 7.5 SC-L and 7.5 SCA-L

Expansion strains of 1-in.-thick (2.5 cm) prisms of 7.5 SC-L and 7.5 SCA-L concretes after 14 days of fog curing are listed in Table 3. As found with the 7.5 SC and 7.5 SCA concretes, there are no significant differences. Expansion-shrinkage curves for  $p = 0.15\%$  and  $p = 0.30\%$  in



50% R.H. are shown in Figure 18a for 7.5 SC-L concretes. The curve for  $p = 0.15\%$  dropped slightly below the zero strain line after 1 yr. Expansion-shrinkage curves for the same steel percentages in 75% R.H. are presented in Figure 18b. Both the curves remained above the zero strain line through the 365-day period.

Comparisons of residual strains of 7.5 SC-L and 7.5 SCA-L concretes are shown in Table 7. As noted before for the 7.5 SC and 7.5 SCA concretes, there are no significant differences, so air-entrainment does not appear to affect the performance of shrinkage-compensating concretes.

Comparisons of expansion-shrinkage data for 7.5 SC and 7.5 SC-L (Tables 3 through 7) show that expansion of 7.5 SC prisms 1-in.-thick (2.5 cm) with  $p = 0.15\%$  (845) is considerably higher than similar prisms of 7.5 SC-L (705); on the other hand, the shrinkage from 14 to 365 days for the 7.5 SC prisms in 50% R.H. is -880 [845 - (-35)] and for 7.5 SC-L prisms is -750 [705 - (-45)]. Corresponding figures for shrinkage in 75% R.H. are -680 and -450. With these relationships for 1-in.-thick (2.5 cm) prisms and the logical assumption that the effects of prism thickness and steel percentage will be same for both types of concrete (7.5 SC and 7.5 SC-L), data for design purposes can be obtained for 7.5 SC-L concretes.

#### Expansion-Shrinkage of 7.5 SCA-SLW Prisms

Expansions of 7.5 SCA-SLW prisms after 14 days of fog curing are listed in line 5 of Table 3. These expansion values represent significant increases over those in the previously reported concretes of lines 1-4. Lightweight concretes, such as 7.5 SCA-SLW, expand more than normal weight concretes for at least two reasons:

- (1) The lightweight aggregate (in this case, coarse expanded shale) absorbs much more mixing water than does the normal weight aggregate. This mixing water is later drawn back into the concrete matrix as the cement hydrates and the interior of the concrete dries. This water increases the humidity inside the concrete and provides more favorable conditions for expansion.[17]

- (2) Lightweight concrete gains in strength at a slower rate than normal weight concrete, due to the basically weaker aggregate; this weaker strength means less resistance to expansion (i.e., more expansion in a given time).

Expansion-shrinkage curves for 1-in.-thick (2.5 cm) prisms in 50% R.H. are shown in Figure 19a. The curve for  $p = 0.15\%$  remains above the zero strain line. Corresponding curves for 1-in.-thick (2.5 cm) prisms in 75% R.H. are presented in Figure 19b. Both curves remain in the plus strain zone throughout the 365-day period. Similar performances are observed for 2- and 4-in.-thick (5.1 and 10.2 cm) prisms in 50% R.H. and 75% R.H., as indicated in Figures 20 and 21.

Residual strains after 365 days are shown in Table 8 and the effects of specimen thickness are presented in Figure 22 in terms of S/V.



Shape of the curves is quite similar to those in Figures 16a, b, and c. It should be noted that although thickness affects the magnitude of residual strain, in 50% R.H. the  $p = 0.15\%$  curve remains above the zero strain line and in 75% R.H. both of the curves are above the zero strain line.

#### Expansion-Shrinkage of 7.5 SCA-LW Prisms

Expansions of 7.5 SCA-LW prisms after 14 days of fog curing are shown in Table 3. As noted previously with regard to the 7.5 SCA-SLW concrete, these expansions are higher than the normal weight aggregate concretes. Causes of the higher expansions are the same as stated for the 7.5 SCA-SLW concrete; in this case, all the aggregate is lightweight and is thus highly absorptive, eventually contributing even more water into the concrete for curing of the cement. Generally, expansions of the 7.5 SCA-LW concrete in Table 3 are higher than those for the 7.5 SCA-SLW concrete, as expected.

Expansion-shrinkage curves for 1-in.-thick (2.5 cm) prisms in 50% R.H. are shown in Figure 23a. The curve for  $p = 0.15\%$  stayed above the zero strain line throughout the 365-day period, and the curve for  $p = 0.30\%$  dipped just below the line toward the end of the period. Expansion-shrinkage curves for 1-in.-thick (2.5 cm) prisms in 75% R.H. are presented in Figure 23b. Both curves remained substantially above the zero strain line.

Expansion-shrinkage curves for 2-in.-thick (5.1 cm) prisms in 50% R.H. are shown in Figure 24a. The curve for  $p = 0.15\%$  stayed above the zero strain line, while the curve for  $p = 0.30\%$  reached the zero strain line at 365 days. As indicated in Figure 24b, both curves in 75% R.H. stayed substantially above the zero strain line.

Expansion-shrinkage curves for 4-in.-thick (10.2 cm) prisms, shown in Figure 25a and b for 50% R.H. and 75% R.H., respectively, are quite similar to those for the 2-in.-thick (5.1 cm) prisms.

Residual strains after 365 days are given in Table 9 for all three thicknesses. Effects of prism thickness upon S/V are shown in Figure 26. These curves, quite similar to previous ones, furnish a ready means for prediction of expected performance of 7.5 SCA-LW concretes in thicknesses from 1 to 12 in. (2.5 to 30.5 cm) for steel percentages of 0.15 and 0.30.

#### SC Mixes With Different Cement Contents

Expansions of the prisms made with these concretes are shown in Table 4. Since it is the cement which causes the expansion, one would expect that the more cement the more expansion, other things being equal. This is verified in Table 4. As expected, the higher the reinforcement, the lower is the expansion for a given prism thickness. Figure 4 shows the effects of cement content on 14-day expansion for 1-in.-thick (2.5 cm) prisms.\*

\* Steel percentage  $p = 0.15\%$ .

Expansion-shrinkage of 1-in.-thick (2.5 cm) prisms of SC mixes with different cement contents in 50% R.H. is presented in Figure 27a for  $p = 0.15\%$ . Note that the rather significant differences in expansion between the 6.3 SC and 11.0 SC at 14 days is greatly reduced after 365 days; i.e., much of the advantage of the higher expansion is lost during the shrinkage period.

Reasons for this are shown in Table 10 which reports shrinkage strains for the SC mixes with different cement contents. Table 10 verifies the long-established axiom that shrinkage increases as the cement content increases. Referring to Figure 27a, the optimum cement content to obtain a residual strain of zero after 365 days would be about 8.5 bags/yd<sup>3</sup>; 9.1 bags/yd<sup>3</sup> would be conservative for the conditions shown (1-in.-thick prisms with  $p = 0.15\%$ ). Figure 27b gives the same curves for 75% R.H. As noted in Figure 27a, the advantage of the higher expansions at higher cement contents is reduced after 365 days but not quite so dramatically as in 50% R.H. All of the curves remained above the zero strain line in 75% R.H.

Table 11 lists residual strains after 365 days for all prisms of the SC mixes with different cement contents. Also included in Table 11 are the pounds per cubic yard equivalents for the bags per cubic yard. Curvilinear relationships for the 1-in.-thick (2.5 cm) prisms are shown in Figure 28. As noted in almost all other concretes in 50% R.H., prisms with  $p = 0.30\%$  dropped below the zero strain line after 365 days, while at least some of those with  $p = 0.15\%$  remained above the zero strain line.

Table 11 also lists residual strains for the same mixes in 75% R.H., and Figure 29 shown the curves for 2-in-thick (5.1 cm) prisms.

#### Compressive Strengths and Young's Moduli

In an earlier CEL report, data were presented which indicated that both compressive strengths and Young's moduli of shrinkage-compensating concretes are equal to or greater than those of portland cement concrete.[18] Further tests have shown that this is true for all the types of concrete used in this study.

#### DESIGN APPLICATIONS

Structurally speaking, it has been shown that shrinkage-compensating concrete can be safely substituted for portland cement concrete, utilizing the same design factors as for portland cement concrete: cement content, water/cement ratio, air-entrainment, steel percentage, etc.[6,7] However, the value of shrinkage-compensating concrete is in its ability to compensate for expected shrinkage and thus avoid shrinkage cracking. Test results make it plain that shrinkage-compensating concrete is effective for its stated purpose only when the steel percentage is fairly low (i.e., less than 0.30%). Effective utilization

of shrinkage-compensating concrete is thus limited to those structures which are lightly reinforced.

For a given structure, once the designer has chosen the thickness, steel percentage, and minimum cement content required for structural safety, he can determine the efficacy of using shrinkage-compensating concrete by determining the following factors: shrinkage to be expected (to be compensated for) and expansion he can expect from different cement contents at the steel percentage chosen, with both factors dependent upon the thickness of the structure and upon environment.

Shrinkage to be expected can be determined from Figures 30 and 31. Shrinkage values used to derive these curves were taken from test data in this report; averages were used to simplify the curves. Since shrinkage is not much different for steel percentages of 0.15% and 0.30%, shrinkage curves in Figures 30 and 31 are independent of steel percentage. Where one shrinkage was slightly higher than the other, as in line 2 of Table 10, the higher value was plotted, thus making these figures conservative. For example, for a structure 6 in. thick made with normal weight 7.5 SC river aggregate concrete to be placed in an environment where the average humidity is 65%, Figure 30a shows shrinkage values of -780, -655, and -540 for 1, 2, and 4 in. thick, respectively. These values, plotted on Figure 31a, result in the dashed curve shown. Shrinkage of a 6-in.-thick structure in 65% R.H. can be expected to be -460 microstrain. If the cement content is higher or lower than 7.5 bags/yd<sup>3</sup>, a multiplication factor for the shrinkage can be obtained from Figure 32 (taken from Table 10), which shows factors for steel percentages of 0.15% and 0.30%.

Having established the amount of expected shrinkage, the design and analysis for use of shrinkage-compensating concrete can be completed by utilizing Figures 33a, b, and c which shows expansion for normal weight, sand-lightweight, and all-lightweight 7.5 SC concretes, respectively. Figures 34 and 35 show effects of cement content on expansions in SC concretes with steel percentage = 0.15%.

#### Design Examples

1. Given: SC normal weight river  
Aggregate concrete = 7.5 bags/yd<sup>3</sup>  
Steel percentage = 0.15%  
Concrete thickness = 6 in.  
Average humidity = 65% R.H.

Analysis: From Figures 30a and 31a, shrinkage = -460 microstrain  
From Figure 33a, expansion = 530 microstrain

Conclusion: Expansion (530) of SC normal weight concrete at 7.5 bags/yd<sup>3</sup> is more than adequate to compensate for shrinkage (-460)



2. Given: Same as for Example 1, except that sand-lightweight aggregates are to be used

Analysis: From Figures 30b and 31b, shrinkage = -380 microstrain  
From Figure 33b, expansion = 565 microstrain

Conclusion: Expansion (565) of SC sand-lightweight concrete is more than adequate to compensate for shrinkage (-380).

3. Given: SC normal weight river  
Aggregate concrete = 7.5 bags/yd<sup>3</sup>  
Steel percentage = 0.15%  
Concrete thickness = 3 in.  
Average humidity = 50% R.H.

Analysis: From Figure 31a, shrinkage = -665 microstrain  
From Figure 33a, expansion = 660 microstrain

Conclusion: Expansion (660) of SC normal weight river aggregate concrete is just adequate to compensate for shrinkage (-665)

4. Given: SC normal weight river  
Aggregate concrete = 7.0 bags/yd<sup>3</sup>  
Steel percentage = 0.15%  
Concrete thickness = 2 in.  
Average humidity = 50% R.H.

Analysis: From Figure 31a, shrinkage for 7.5 bags/yd<sup>3</sup> and 2 in. thickness = -740 microstrain; since cement content is 7.0 bags/yd<sup>3</sup>, obtain multiplication factor from Figure 32:  $0.96 \times (-740) = -710$  microstrain  
From Figure 34, plot expansions for 7.0 bags/yd<sup>3</sup> onto Figure 35, as shown by the dashed line; expansion for 2 in. thickness = 675 microstrain

Conclusion: Expansion (675) of 7.0 SC normal weight river aggregate concrete is not adequate to compensate for shrinkage (-710). Alternatives are: (1) use higher cement content or (2) use lower steel percentage. Assuming the steel percentage to be minimum for code, adjust by obtaining proper cement content to compensate for shrinkage of -710 microstrain. From Figure 34, adjust cement content to 7.5 bags/yd<sup>3</sup>, providing expansion of 730 microstrain. To check adequacy of expansion, see Figure 31a to obtain shrinkage for 7.5 bags/yd<sup>3</sup> = -740 microstrain.

Final Conclusion: Expansion (730) is close enough to the shrinkage (-740) to be considered adequate.

Other combinations of data for use in design can be prepared from the data in this report. The example designs were presented to illustrate methods. Similar design relationships can be developed for SC concretes made with crushed limestone aggregates.

#### CONCLUSIONS

1. Shrinkage-compensating concrete can be designed and utilized to adequately compensate for shrinkage; due consideration must be given to cement content, steel percentage, thickness, adequate curing, and ambient humidity at the structure.

2. Steel percentages less than 0.30% seem to be optimum for most design situations, although in some cases cement content can be increased to overcome deficient expansion.

#### RECOMMENDATIONS

1. Shrinkage-compensating concrete should be used to eliminate or minimize shrinkage cracking in designs which incorporate low steel percentages (less than 0.30%). Tables and figures in this report should be used to determine interrelationships between cement content, steel percentage, thickness, environment, and shrinkage. It should be noted that this recommendation applies only to structural applications, not to slabs-on-grade.

#### ACKNOWLEDGEMENTS

Experimental testing and reduction and plotting of data were conducted by J. G. Crahan, J. R. Mooney, Jr., and V. Hernandez. The author gratefully acknowledges the cooperation of Mr. W. P. Liljestrom of the Chemically Prestressed Concrete Corporation and of Mr. C. Taylor Test of the Southwestern Portland Cement Company.

#### REFERENCES

1. Portland Cement Association. Design and control of concrete mixtures, Eleventh Edition. Skokie, Ill., Jul 1968, pp. 12-18.
2. W. Czernin. Cement chemistry and physics for civil engineers. New York, N.Y., Chemical Publishing Company, 1962, pp. 1-27.

3. A. Klein and G. E. Troxell. "Studies of calcium sulfoaluminate admixtures for expansive cements," in Proceedings, American Society for Testing and Materials, vol 58, 1958, pp. 989-1008.
4. A. Klein and B. Bresler. "A Review of Research on Expansive Cement Concretes, Part I, Introduction," in Proceedings, The Structure of Concrete and Its Behaviour Under Load, London, Eng, Cement and Concrete Association, 1968. pp. 467-472.
5. University of California, College of Engineering, Division of Structural Engineering and Structural Mechanics. Report No. 66-7; Expansive cements and expanding concretes, by S. Aroni, M. Polivka, and B. Bresler. Berkeley, Calif., Jul 1966.
6. "Expansive cement concretes - present state of knowledge," Journal of American Concrete Institute, vol 67, no. 8, Aug 1970, pp. 583-610.
7. ———. ACI Standard 223-77: "Recommended practice for the use of shrinkage-compensating concrete," March 1977.
8. Chemically Prestressed Concrete Corporation. Tentative specification for ChemComp cement. Van Nuys, Calif, Dec 1968.
9. M. Polivka and V. Bertero. "Factors affecting the properties of expanding concrete," in Proceedings, The Structure of Concrete and Its Behaviour Under Load, The Cement and Concrete Association, London, 1968, pp 487-492.
10. S. Aroni and M. Polivka. "Effect of expanded shale aggregate on properties of expansive cement concrete," in Proceeding RILEM Symposium on Lightweight Aggregate Concretes, Budapest, Hungary, Mar 1967.
11. V. Bertero and M. Polivka. "Effect of degree of restraint on mechanical behavior of expansive concrete," in Proceedings of the American Society for Testing and Materials, Vol. 64, 1964, pp 797-815.
12. P. Klieger and N. R. Greening. "Utility of expansive cement," in Proceedings of Fifth Symposium on Chemistry of Cement, Tokyo, Japan, Oct 1968. Also published under the title "Properties of Expansive Cement Concretes" by the Portland Cement Association R&D Laboratories, Skokie, Illinois as R&D Ser. 1370-1, Oct 1969.
13. A. H. Gustaferrero, N. R. Greening and P. Klieger. "Expansive concretes - laboratory tests of freeze-thaw and surface scaling resistance," Journal of the Portland Cement Association R&D Laboratories. Vol. 8, No. 1, January 1966, pp 10-36. (Research Department Bulletin 190).
14. Naval Civil Engineering Laboratory. Technical Report R-704: Creep and shrinkage of reinforced thin-shell concrete, by J. R. Keeton. Port Hueneme, Calif., Nov 1970.



15. \_\_\_\_\_. Technical Report R-333-I: Study of creep in concrete, phase 1 (I-beam), by J. R. Keeton. Port Hueneme, Calif., Jan 1965.
16. T. C. Hansen and A. H. Mattock. "Influence of size and shape of member on the shrinkage and creep of concrete," Journal of the American Concrete Institute, vol 63, no. 2, Feb 1966, pp 267-290.
17. Naval Civil Engineering Laboratory. Technical Report R-692: Permeability studies of reinforced thin-sheer concrete, by John R. Keeton. Port Hueneme, Calif., Aug 1970.
18. \_\_\_\_\_. Technical Note N-1264: Expansive cement concretes for Naval Construction - first report, by John R. Keeton, Port Hueneme, Calif., Mar 1973.

Table 1. Thin Shell Prisms of Shrinkage-Compensating Concrete Used in Research Program

Cement Content		Prism <sup>a</sup> Size	Mesh Reinforcement	Relative Humidity in Storage Environment at 73F
lb/yd <sup>3</sup>	bags/yd <sup>3</sup>	in.	%	%
A. River Aggregate, Non-Air-Entrained Concrete				
592	6.3	1 x 5 1 x 10 2 x 5 2 x 5	0.30 0.15 0.15 0.30	50,75 50,75 50,75 50,75
705	7.5	1 x 5 1 x 10 2 x 5 2 x 5 2 x 5 4 x 5 4 x 5 4 x 5 4 x 5 4 x 5	0.0,0.30,0.47,0.503,0.785 0.15 0.30,0.503,0.785 0.0 0.15,0.44 0.30 0.785 0.0 0.15,0.44 0.503	25,50,75,100 50,75 25,50,75,100 50,75,100 50,75 25,50,75,100 25,50,100 50,75,100 50,75 75
776	8.25	1 x 5 1 x 10 2 x 5	0.30 0.15 0.15,0.30	50,75 50,75 50,75
855	9.1	1 x 5	0.30	50
964	10.25	1 x 5	0.30	50
1,034	11.0	1 x 5	0.30	50

continued

Table 1 (Cont'd)

Cement Content		Prism <sup>a</sup> Size	Mesh Reinforcement	Relative Humidity in Storage Environment of 73F
lb/yd <sup>3</sup>	bags/yd <sup>3</sup>	in.	%	%
B. River Aggregate, Air-Entrained <sup>b</sup> Concrete				
705	7.5	1 x 5	0.30,0.47	25,50,75,100
		1 x 5	0.503	25,50,100
		1 x 5	0.0	100
		1 x 10	0.15	50,75
C. Crushed Limestone Aggregate, Non-Air-Entrained Concrete				
705	7.5	1 x 5	0.30,0.47	50,75
		1 x 5	0.0	75
		1 x 10	0.15	50,75
		2 x 5	0.0,0.15,0.30	50,75
D. Crushed Limestone Aggregate, Air-Entrained <sup>b</sup> Concrete				
705	7.5	1 x 5	0.30,0.47	50,75
		1 x 5	0.0	100
		1 x 10	0.15	50,75
		2 x 5	0.15,0.30	50,75
		2 x 5	0.0	100

continued



Table 1 (Cont'd)

Cement Content		Prism <sup>a</sup> Size	Mesh Reinforcement	Relative Humidity in Storage Environment of 73F
lb/yd <sup>3</sup>	bags/yd <sup>3</sup>	in.	%	%
E. River Sand and Lightweight Coarse Aggregate, Air-Entrained <sup>b</sup> Concrete				
705	7.5	1 x 5	0.30	50,75,100
		1 x 10	0.15	50,75,100
		2 x 5	0.15	50,75
		2 x 5	0.30	50,75,100
		4 x 5	0.15,0.30	50,75
F. All Lightweight Aggregate, Air-Entrained <sup>b</sup> Concrete				
705	7.5	1 x 5	0.30	50,75
		1 x 10	0.15	50,75
		1 x 10	0.0	75
		2 x 5	0.15	50,75
		2 x 5	0.30	50,75,100
		4 x 5	0.15,0.30	50,75

<sup>a</sup>Prism measurements refer to thickness and width; all thin-shell prisms were 12 in. long.

<sup>b</sup>Entrained air content was 6 to 8%.

Table 2. Reinforcement Percentages Using Welded Wire Fabric

Prism Size <sup>a</sup> (in.)	Number of Pieces of Fabric	Mesh Spacing, (in.)	Wire Gage No.	Reinforcement <sup>b</sup> (%)
1 x 10	1	4 x 4	14	0.15
1 x 5	1	2 x 2	14	0.30
1 x 5	1	2 x 2	12	0.47
1 x 5	1	1 x 1	14	0.50
1 x 5	1	1 x 1	12	0.78
2 x 5	1	2 x 2	14	0.15
2 x 5	2	2 x 2	14	0.30
2 x 5	2	2 x 2	12	0.44
2 x 5	2	1 x 1	14	0.50
2 x 5	2	1 x 1	12	0.78
4 x 5	2	2 x 2	14	0.15
4 x 5	4	2 x 2	14	0.30
4 x 5	4	2 x 2	12	0.44
4 x 5	4	1 x 1	14	0.50
4 x 5	4	1 x 1	12	0.78

<sup>a</sup> Prism measurements shown refer to thickness and width; all thin-shell prisms were 12 in. long

<sup>b</sup> Reinforcement percentage = the total cross-sectional area of the horizontal wires at the end of the prism ÷ the total cross-sectional area of the prism, viewed from the end.

Table 3. Expansion Strains of Prisms Made With Concrete Mixes Containing 7.5 Bags/yd<sup>3</sup> of Cement, After 14 Days of Fog Curing

Line. No.	Concrete Mix	Expansion Strains <sup>a</sup> With Prism Thicknesses of--								
		1 in.			2 in.			4 in.		
		With Steel Reinforcement (%) of--								
		0	0.15	0.30	0	0.15	0.30	0	0.15	0.30
1	7.5 SC	1,010	845	630	860	730	560	705	610	555
2	7.5 SCA	925	775	645	None	None	None	None	None	None
3	7.5 SC-L	830	705	550	None	None	None	None	None	None
4	7.5 SCA-L	865	705	510	None	None	None	None	None	None
5	7.5 SCA-SLW	1,115	930	725	None	815	630	None	670	525
6	7.5 SCA-LW	1,205	980	710	None	860	665	None	745	610

<sup>a</sup> Expansion strains are in microstrain, average of at least three specimens

Table 4. Expansion Strains of Prisms Made With SC Mixes Containing Different Amounts of Cement,<sup>a</sup> After 14 Days of Fog Curing

Line No.	Concrete Mix	Expansion Strains <sup>b</sup> With Prism Thicknesses of--					
		1 in.			2 in.		
		With Steel Reinforcement (%) of --					
		0	0.15	0.30	0	0.15	0.30
1	6.3 SC	835	710	505	None	565	380
2	7.5 SC	1,010	845	630	None	730	560
3	8.25 SC	1,090	915	700	None	810	625
4	9.1 SC	1,160	985	765	None	885	685
5	10.25 SC	1,245	1,075	850	None	975	745
6	11.0 SC	1,295	1,125	905	None	1,025	775

<sup>a</sup> All mixes made with river aggregate.

<sup>b</sup> Expansion strains are in microstrain, averages of at least three specimens.



Table 5. Expansion Strains of Prisms Made With  
7.5 SC Mixes With Different Steel Percentages<sup>a</sup>,  
After 14 Days of Fog Curing

Steel Percentage	Expansion Strains <sup>b</sup> With Prism Thickness of--		
	1 in.	2 in.	4 in.
0	1,010	860	705
0.15	845	730	610
0.22	750 <sup>c</sup>	645 <sup>c</sup>	555 <sup>c</sup>
0.30	630	560	485
0.44	515 <sup>c</sup>	470 <sup>c</sup>	385
0.47	495	455 <sup>c</sup>	370 <sup>c</sup>
0.50	480	440	355
0.78	390	340	265

<sup>a</sup>All mixes made with river aggregate.

<sup>b</sup>Expansion Strains are in microstrain, averages of at least 3 specimens.

<sup>c</sup>Interpolated values.

Table 6. Residual Microstrains in 7.5 SC Prisms  
After 365 Days of Drying

Prism Thickness, in.	Residual Strains With Steel Reinforcement of--							
	0%	0.15%	0.22%	0.30%	0.44%	0.47%	0.50%	0.78%
A. In 25% R.H.								
1	60	-140 <sup>a</sup>	-270 <sup>a</sup>	-360	-495 <sup>a</sup>	-515	-535	-680
2	35 <sup>a</sup>	-95 <sup>a</sup>	-175 <sup>a</sup>	-280	-440 <sup>a</sup>	-460 <sup>a</sup>	-480	-600
4	10 <sup>a</sup>	-60 <sup>a</sup>	-120 <sup>a</sup>	-230	-390 <sup>a</sup>	-415 <sup>a</sup>	-435 <sup>a</sup>	-545
B. In 50% R.H.								
1	150	-35	-135 <sup>a</sup>	-220	-335 <sup>a</sup>	-355	-375	-500
2	110	-10	-70	-170	-305	-325 <sup>a</sup>	-350	-480
4	70	0	-50 <sup>a</sup>	-130	-285	-310 <sup>a</sup>	-330 <sup>a</sup>	-455
C. In 75% R.H.								
1	300	165	55 <sup>a</sup>	-30	-145 <sup>a</sup>	-165	-180	-290
2	240	135	80	-10	-120	-130 <sup>a</sup>	-150	-250
4	180	110	75 <sup>a</sup>	15	-100	-115 <sup>a</sup>	-130	-215
D. In 100% R.H.								
1	1,095	920	820 <sup>a</sup>	695	565 <sup>a</sup>	545	525	420
2	980	830	745 <sup>a</sup>	655	540 <sup>a</sup>	520 <sup>a</sup>	500	390
4	875	765 <sup>a</sup>	705 <sup>a</sup>	625	510 <sup>a</sup>	490 <sup>a</sup>	470 <sup>a</sup>	365

<sup>a</sup>Interpolated

Table 7. Residual Microstrains of 1-in.-Thick Prisms of 7.5 SC-L and 7.5 SCA-L Concretes After 365 days.

Concrete Mix	Residual Microstrains in--			
	50% R.H.		75% R.H.	
	With Steel Reinforcement of--			
	0.15%	0.30%	0.15%	0.30%
7.5 SC-L	-45	-180	255	65
7.5 SCA-L	-25	-210	255	30

Table 8. Residual Microstrains in 7.5 SCA-SLW Prisms After 365 Days

Prism Thickness, in.	Residual Microstrains in--			
	50% R.H.		75% R.H.	
	Steel Reinforcement of--			
	0.15%	0.30%	0.15%	0.30%
1	50	-155	265	85
2	75	-110	285	115
4	115	- 60	315	150



Table 9. Residual Microstrains in 7.5 SCA-LW Prisms  
After 365 Days

Prism Thickness, in.	Residual Microstrain in--			
	50% R.H.		75% R.H.	
	Steel Reinforcement of--			
	0.15%	0.30%	0.15%	0.30%
1	120	- 40	345	120
2	165	0	360	150
4	215	40	390	185

Table 10. Shrinkage Strains of SC Mixes With  
Different Cement Contents (14 Days to 365 Days)

Cement Content		Shrinkage Strains <sup>a</sup> in--							
		50% R.H.				75% R.H.			
		1 in. Thick		2 in. Thick		1 in. Thick		2 in.	Thick
		at Steel Reinforcement of--							
bags/yd <sup>3</sup>	lb/yd <sup>3</sup>	0.15%	0.30%	0.15%	0.30%	0.15%	0.30%	0.15%	0.30%
6.3	592	-830	-815	-650	-635	-650	-635	-505	-480
7.5	705	-880	-850	-740	-730	-680	-660	-595	-570
8.25	776	-920	-885	-785	-760	-715	-680	-640	-595
9.1	855	-965	-920	-825	-785	-750	-700	-685	-620
10.25	964	-1,030	-965	-890	-805	-800	-735	-740	-645
11.0	1,034	-1,070	-1,005	-925	-815	-830	-765	-770	-645

<sup>a</sup> Microstrain, shown as negative to indicate direction.

Table 11. Residual Microstrains in SC Mixes With  
Different Cement Contents After 365 Days

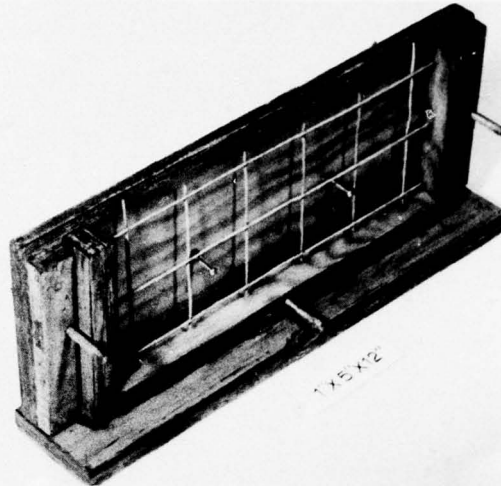
Cement Content		Residual Microstrains in--								
		50% R.H.			75% R.H.					
		1 in. Thick	2 in. Thick	1 in. Thick	2 in. Thick	1 in. Thick	2 in. Thick	1 in. Thick	2 in. Thick	1 in. Thick
		Steel Reinforcement of--								
bags/cu yd	lb/cu yd	0.15%	0.30%	0.15%	0.30%	0.15%	0.30%	0.15%	0.30%	0.30%
6.3	592	-120	-310	-85	-255	60	-130	60	-100	
7.5	705	-35	-220	-10	-170	165	-30	135	-10	
8.25	776	-5	-185	25	-135	200	20	170	30	
9.1	855	20	-150	60	-100	235	65	200	65	
10.25	964	45	-115	85	-60	275	115	235	100	
11.0	1,034	55	-100	100	-40	295	140	255	120	



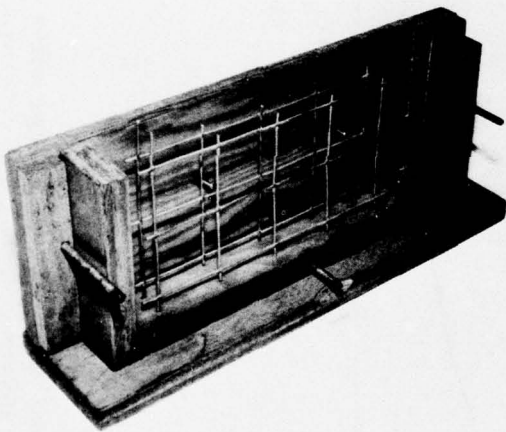
Figure 1. Prismatic test specimens.



(a) 1 in. thick.



(b) 2 in. thick.



(c) 4 in. thick.

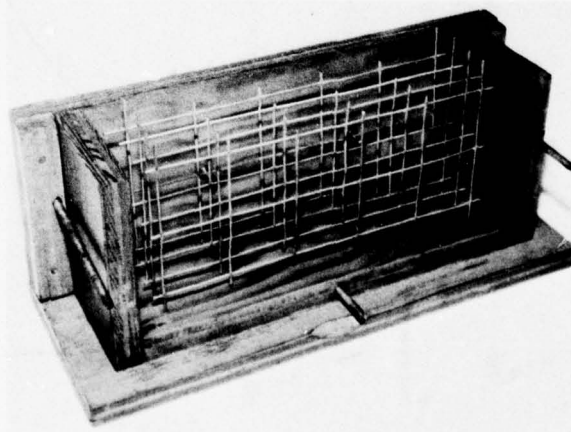


Figure 2. Forms for prisms 5 in. wide and 12 in. long, showing reinforcement.

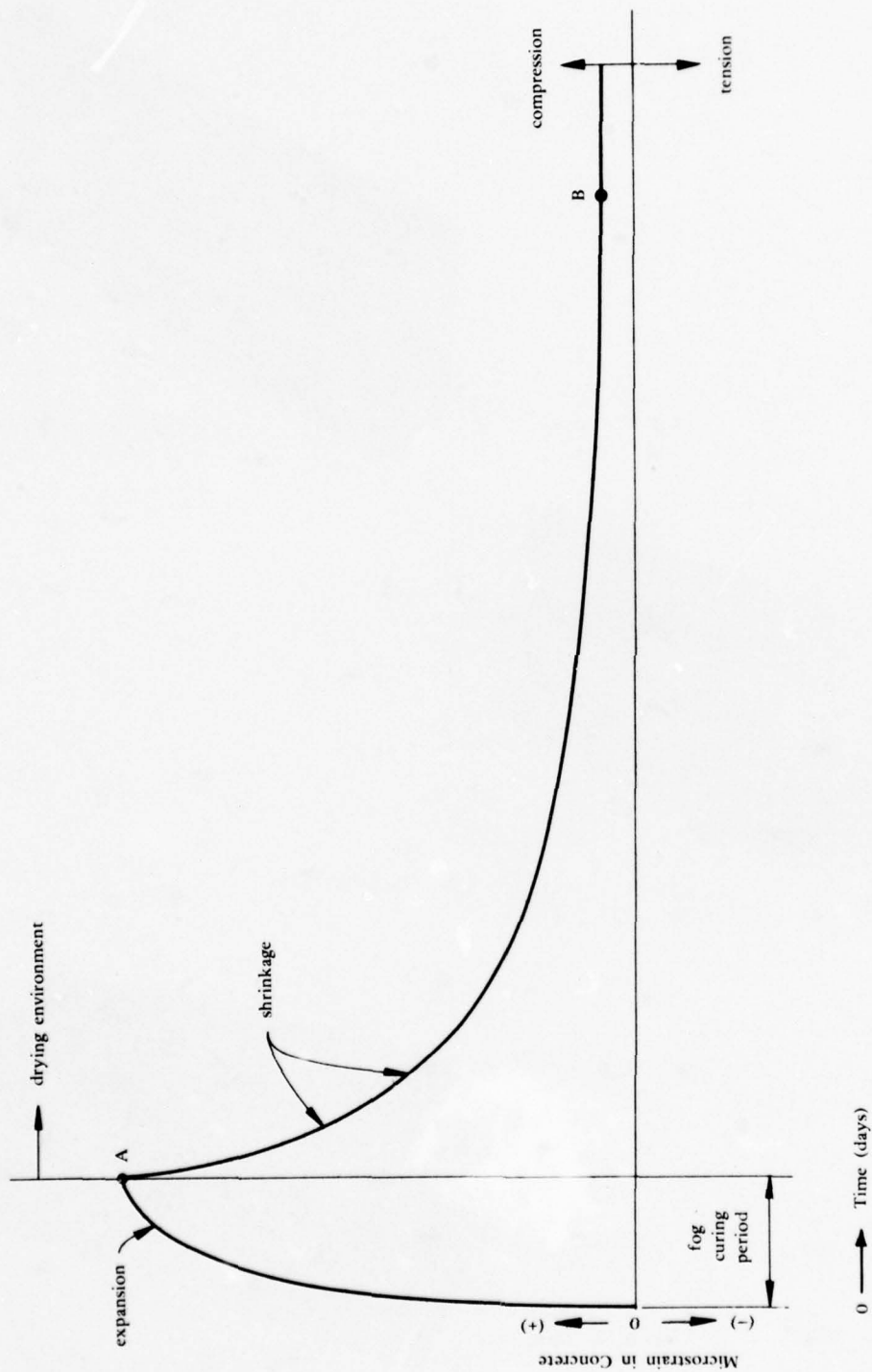


Figure 3. Ideal expansion-shrinkage curve for restrained shrinkage-compensating concrete.

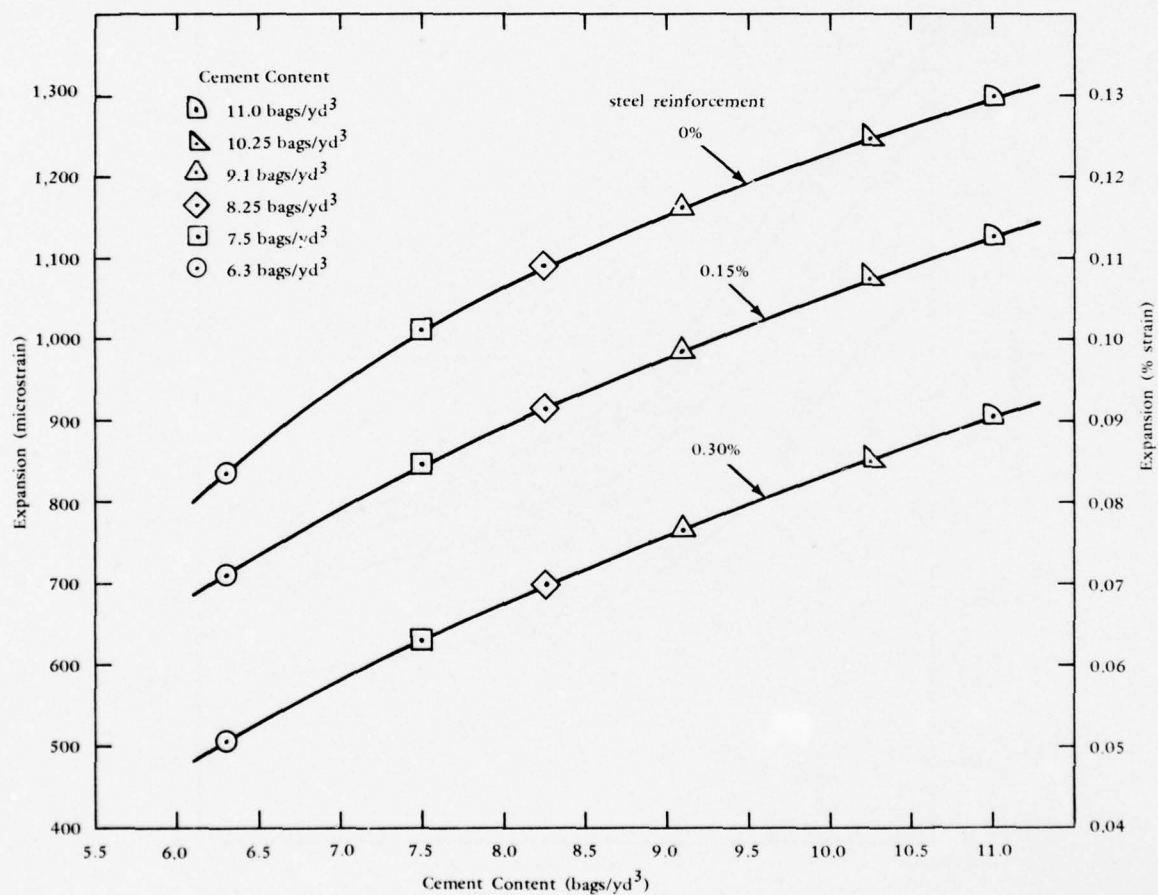


Figure 4. Expansion strains of 1-in.-thick prisms of 7.5 SC concrete after 14 days of fog curing, based on cement content.



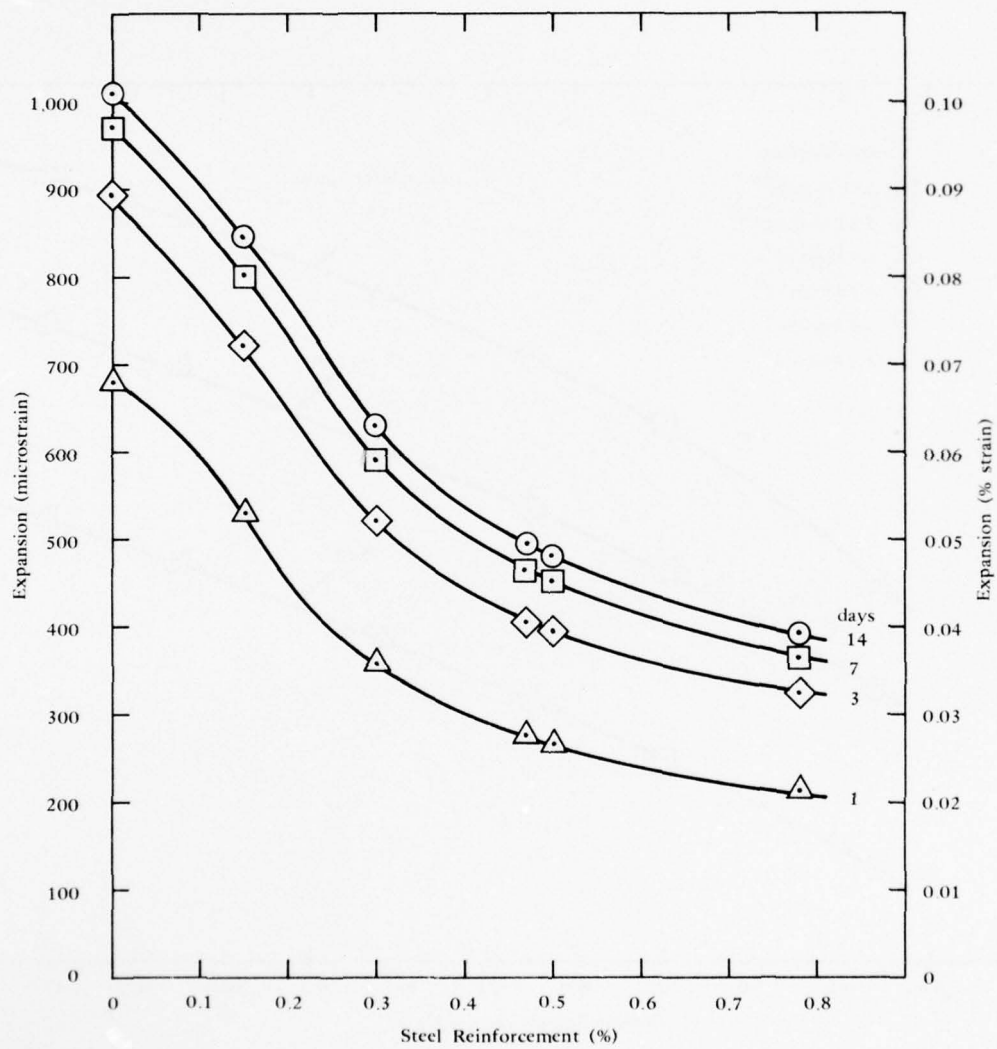


Figure 5. Expansion strains of 1-in.-thick prisms of 7.5 SC concrete during 14 days of fog curing, based on steel reinforcement percentage.

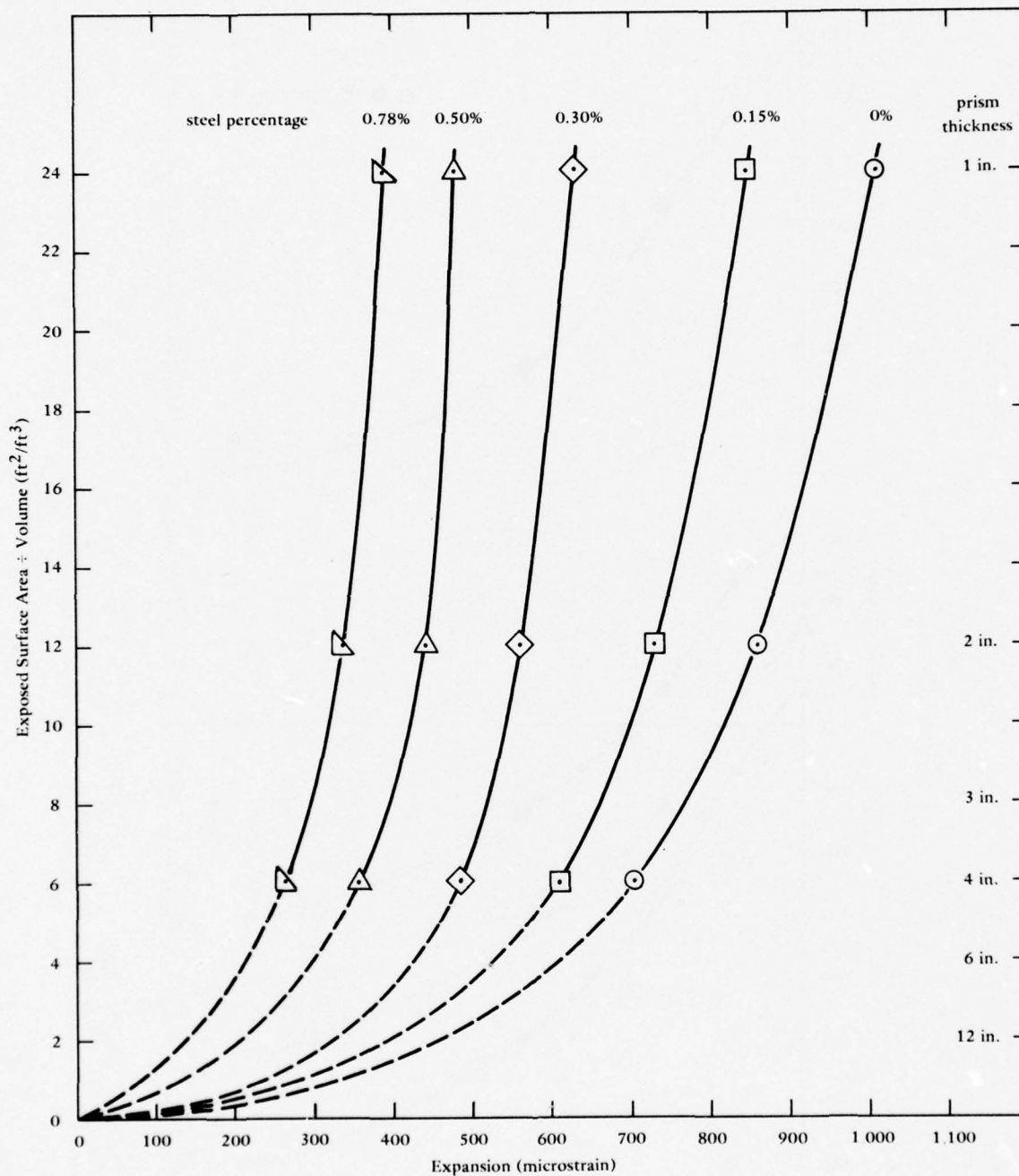


Figure 6. Expansion as a function of surface-to-volume (S/V) ratio, 7.5 SC concrete, after 14 days of fog curing.

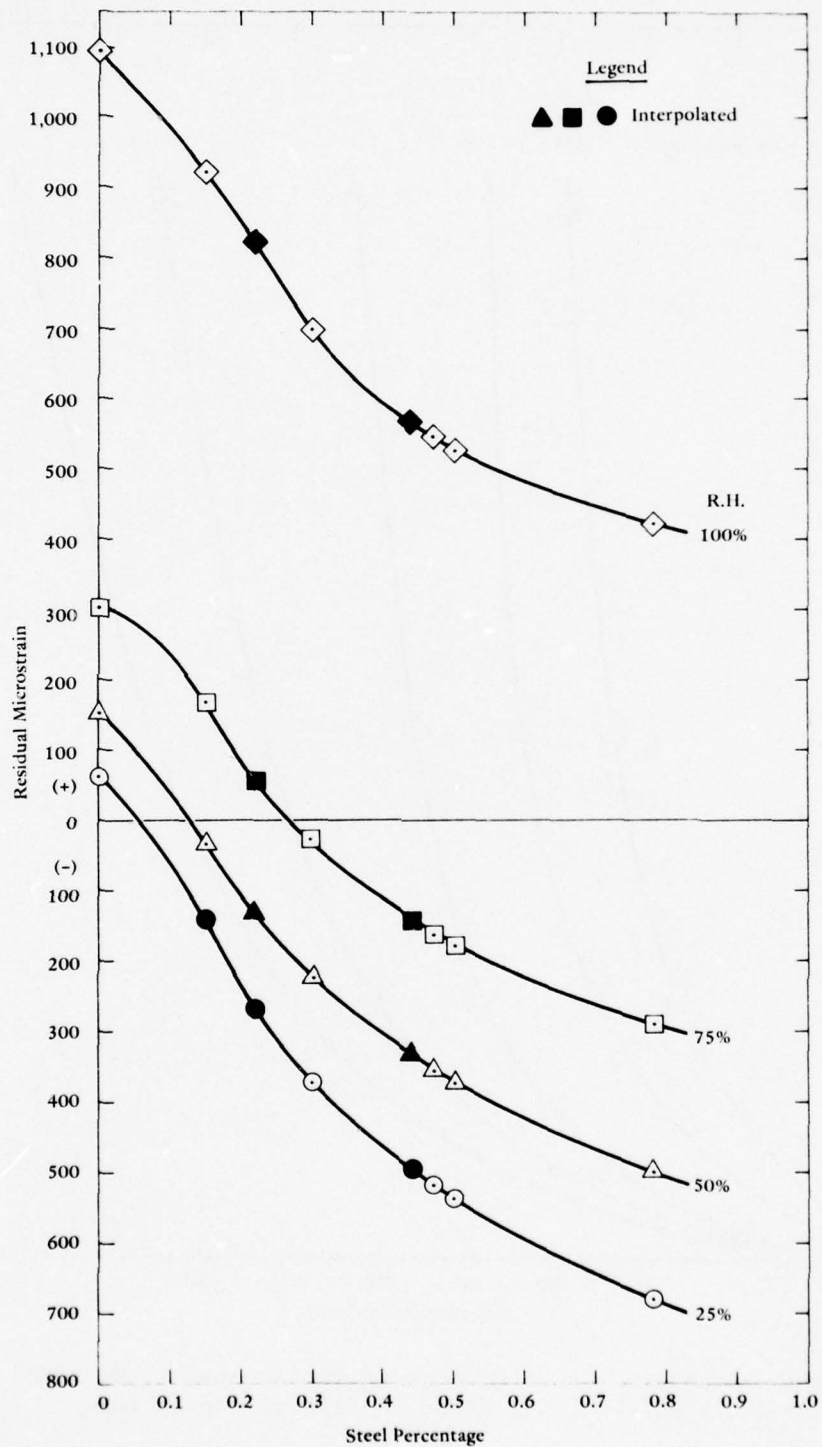
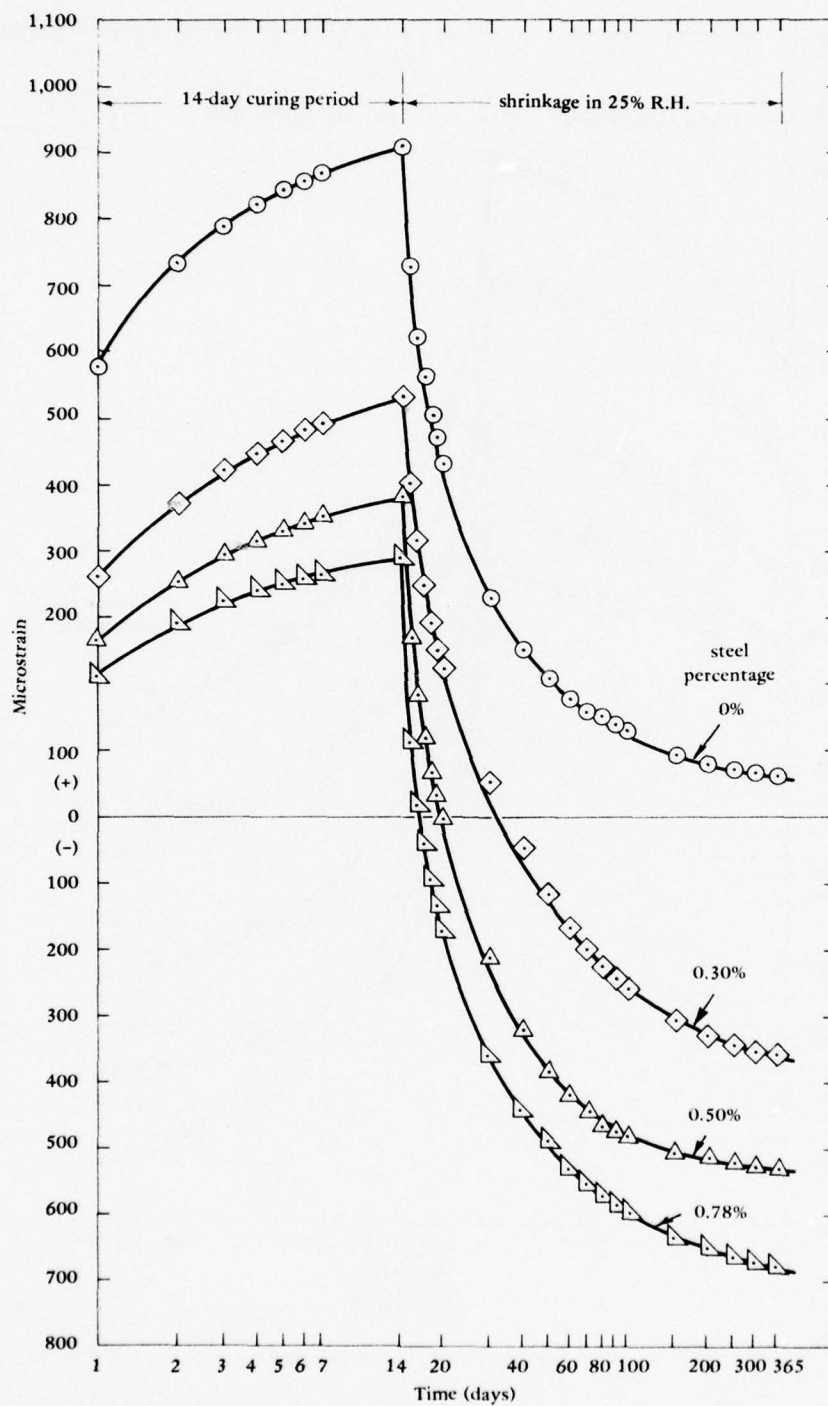


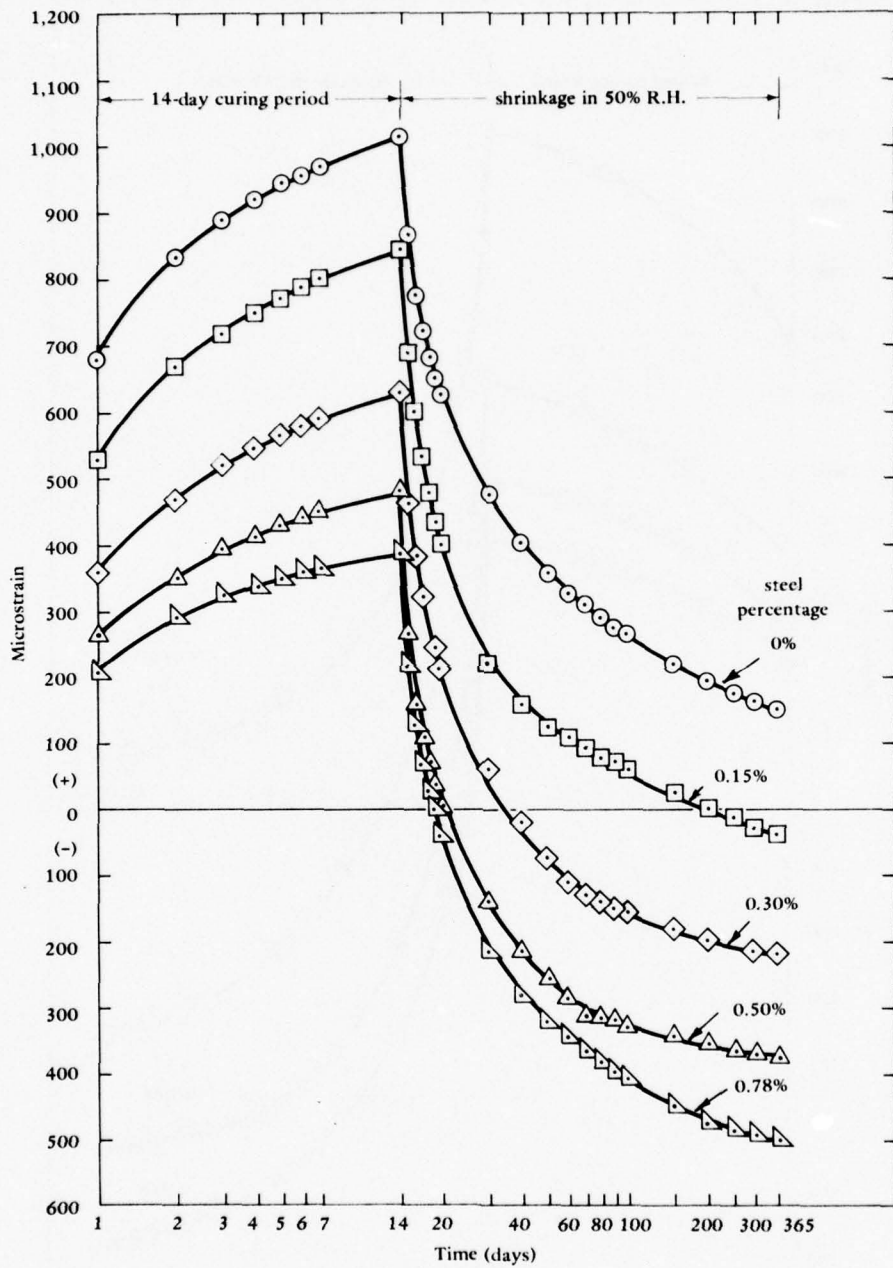
Figure 7. Strain in 1-inch thick prisms of 7.5 SC concrete after 365 days in controlled environments.





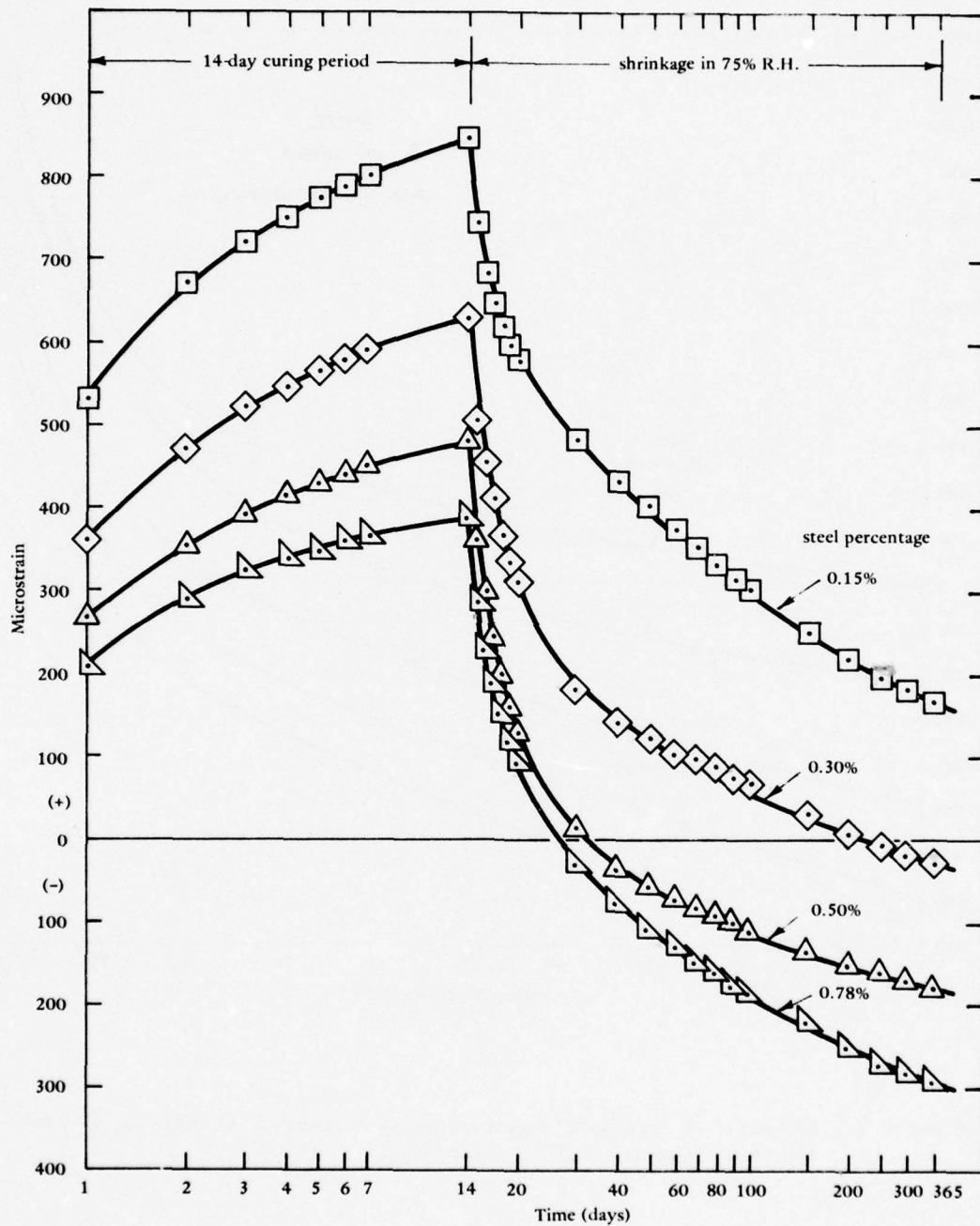
(a) 25% R.H.

Figure 8. Expansion-shrinkage of 1-in.-thick prisms of 7.5 SC concrete.



(b) 50 R.H.

Figure 8. Continued



(c) 75% R.H.

Figure 8. Continued



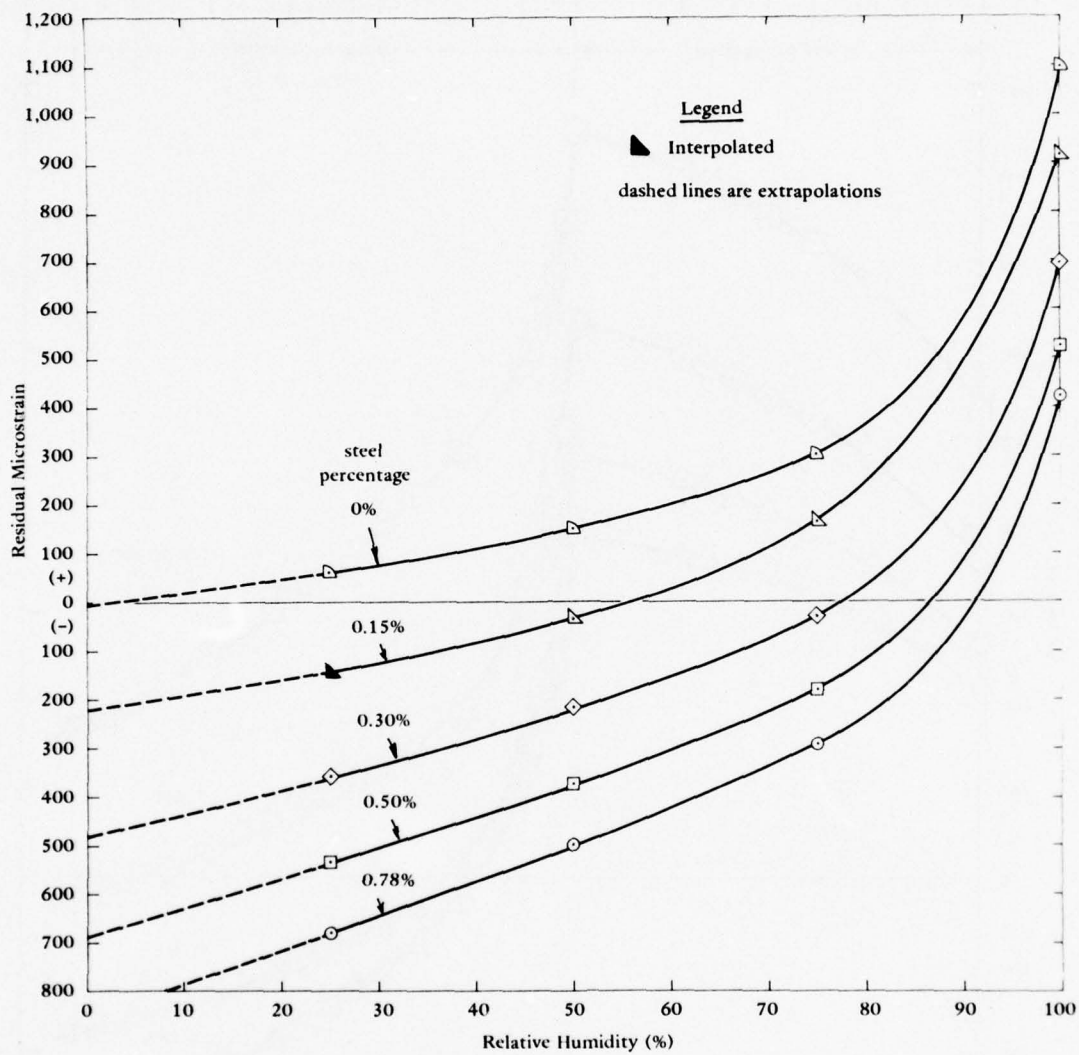


Figure 9. Effects of humidity upon 365-day residual strain in 1-inch-thick prisms of 7.5 SC concrete.

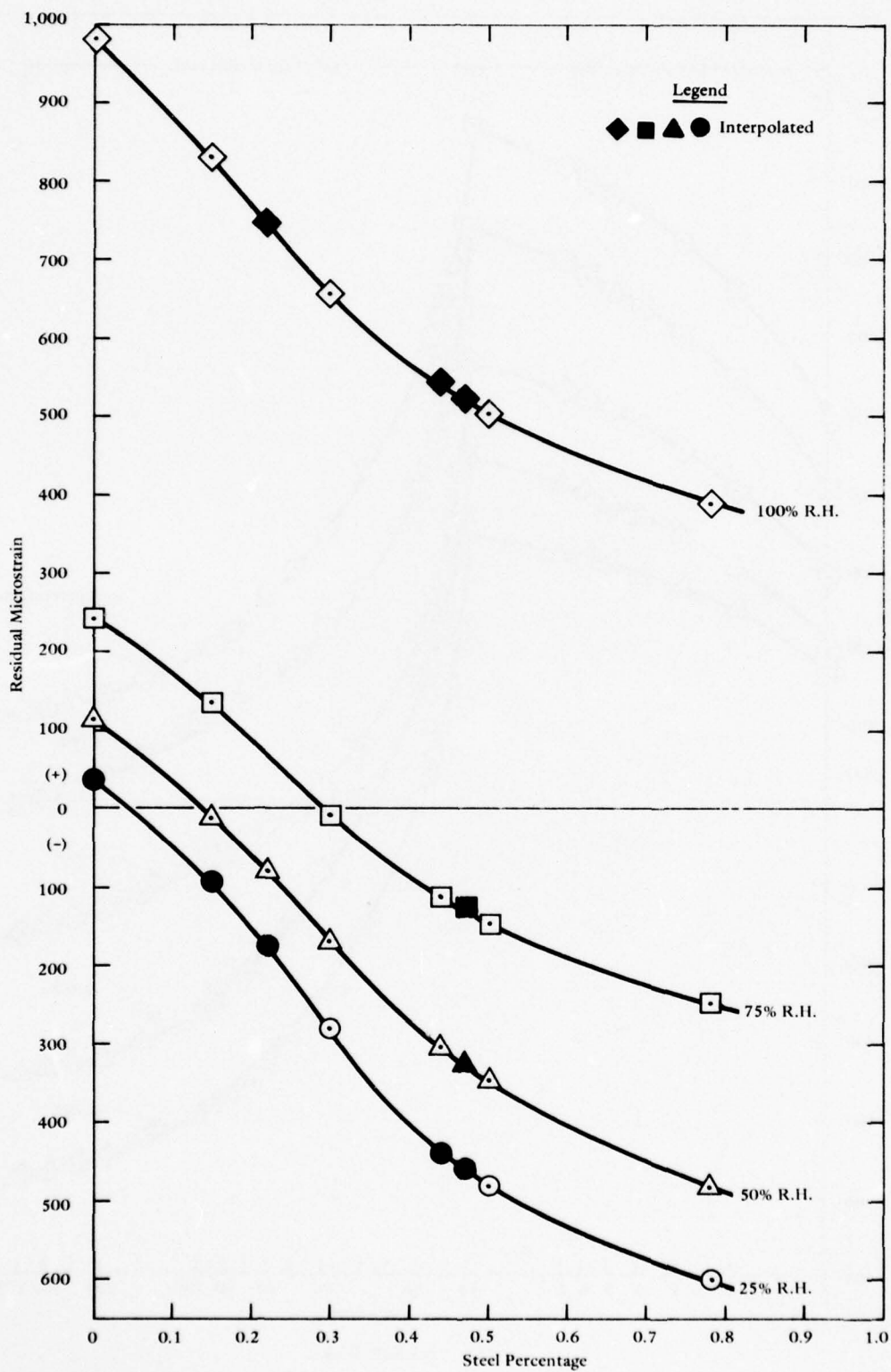
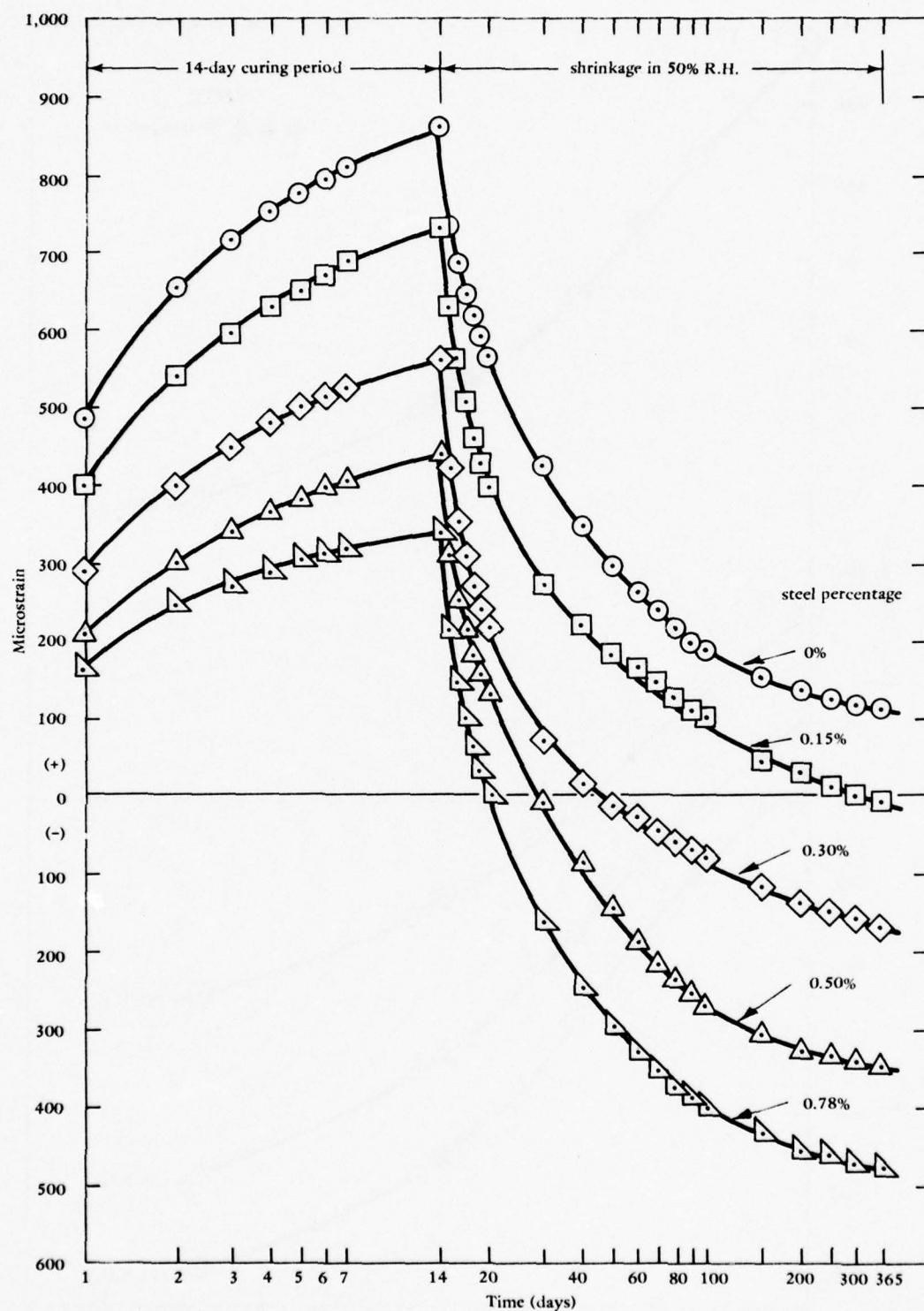
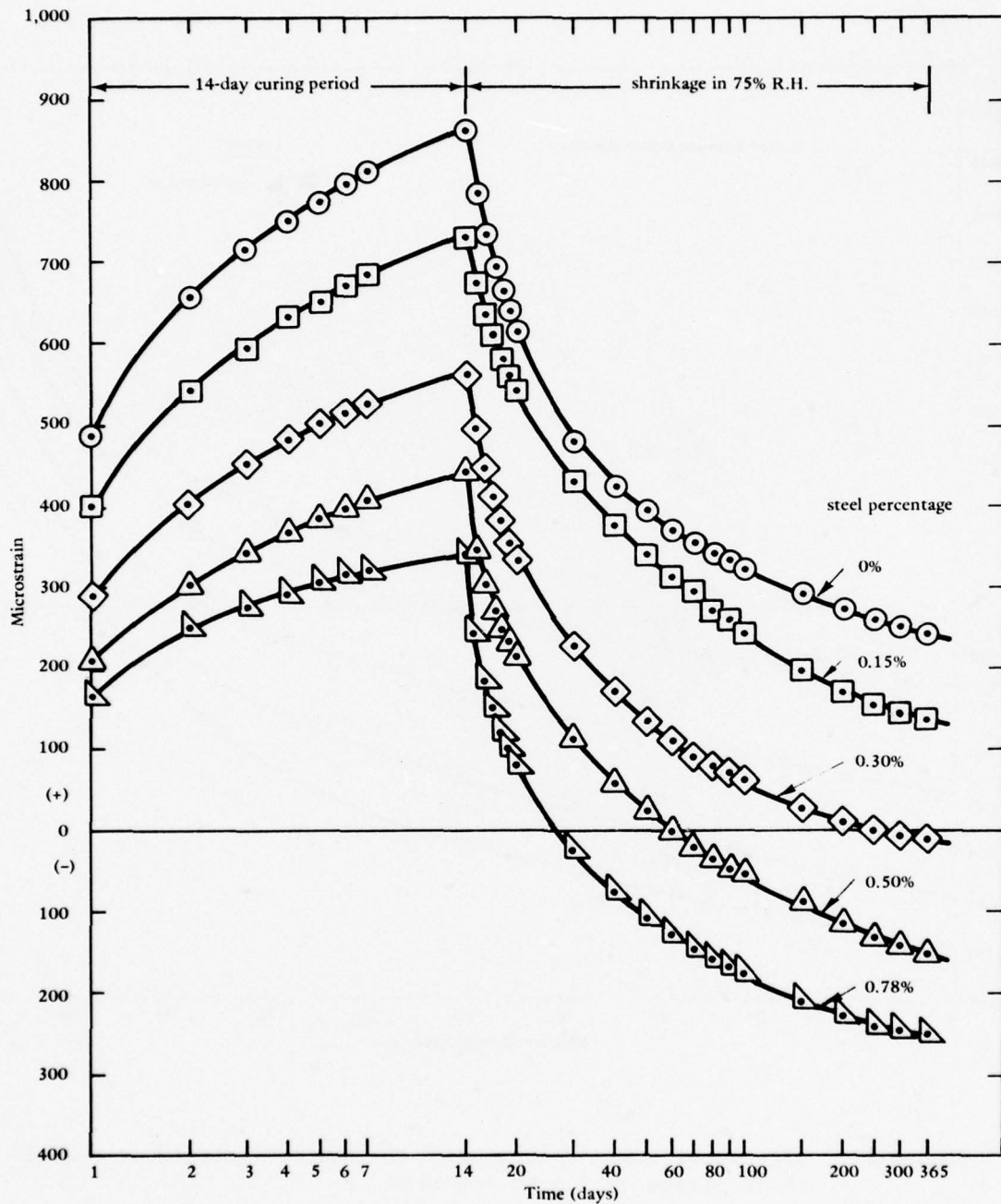


Figure 10. Strain in 2-in.-thick prisms of 7.5 SC concrete after 365 days in controlled environments.



(a) 50% R.H.

Figure 11. Expansion-shrinkage of 2-in.-thick prisms of 7.5 SC concrete.



(b) 75% R.H.

Figure 11. Continued



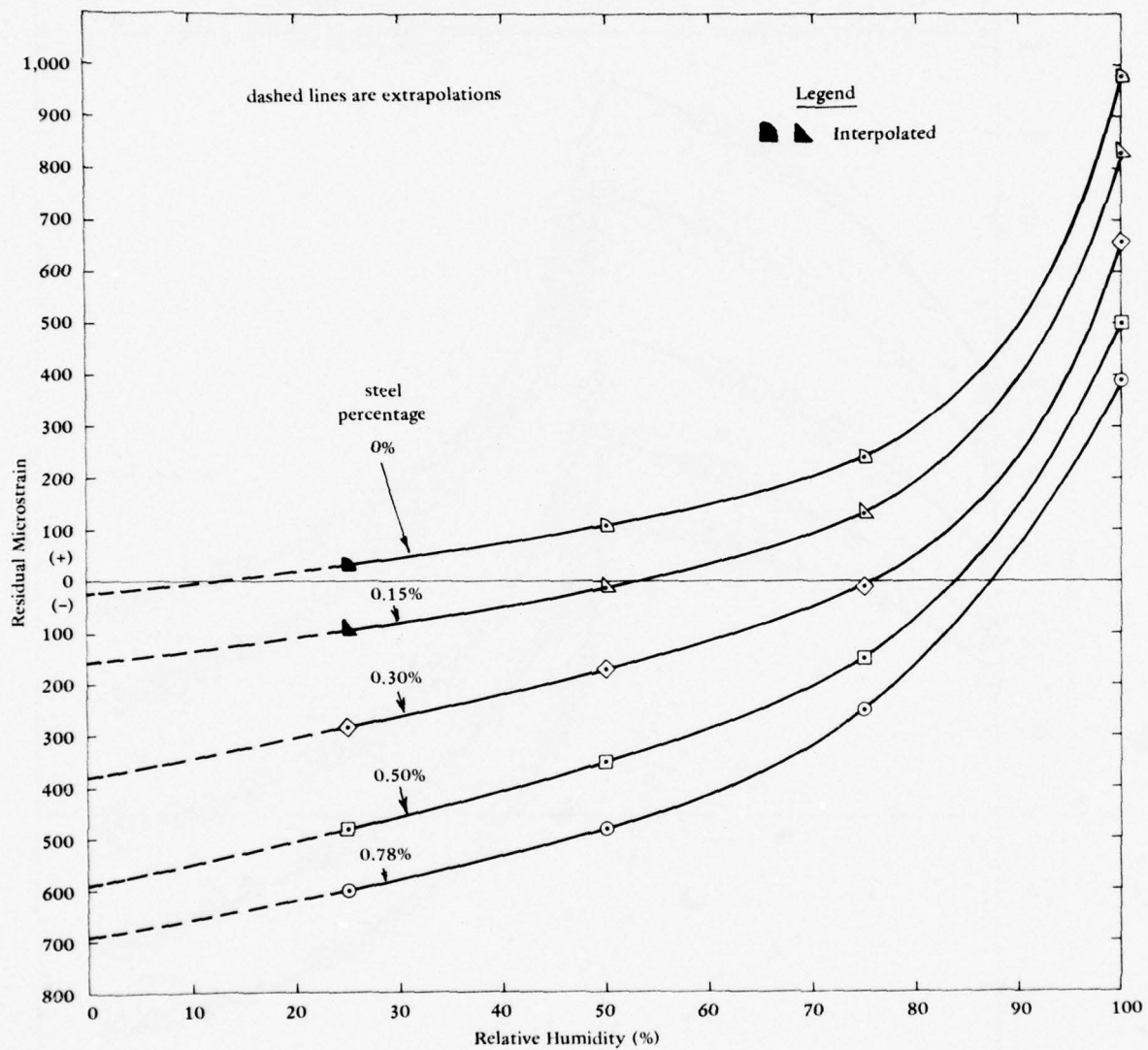


Figure 12. Effects of humidity upon 365-day residual strain in 2-inch-thick prisms of 7.5 SC concrete.

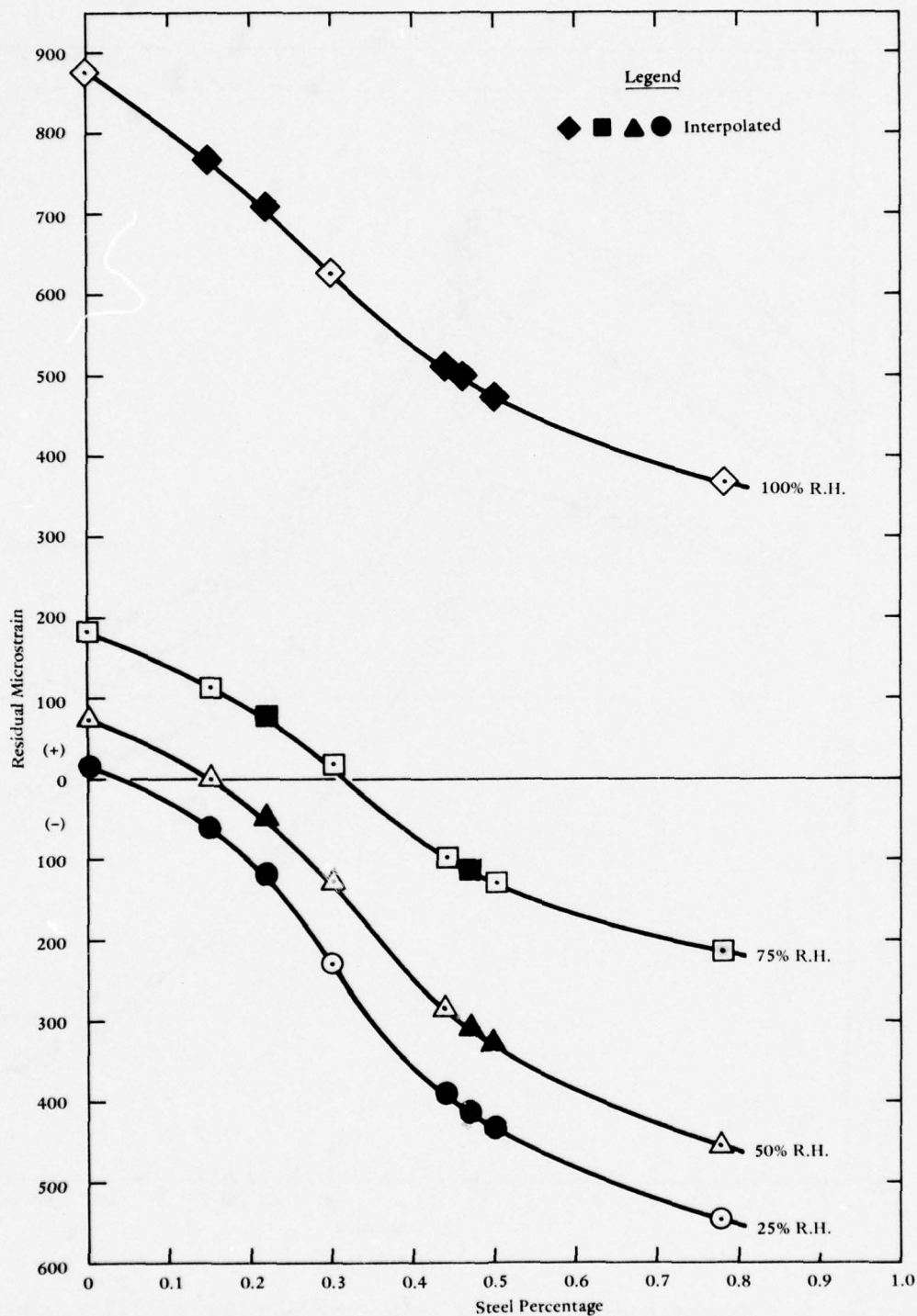
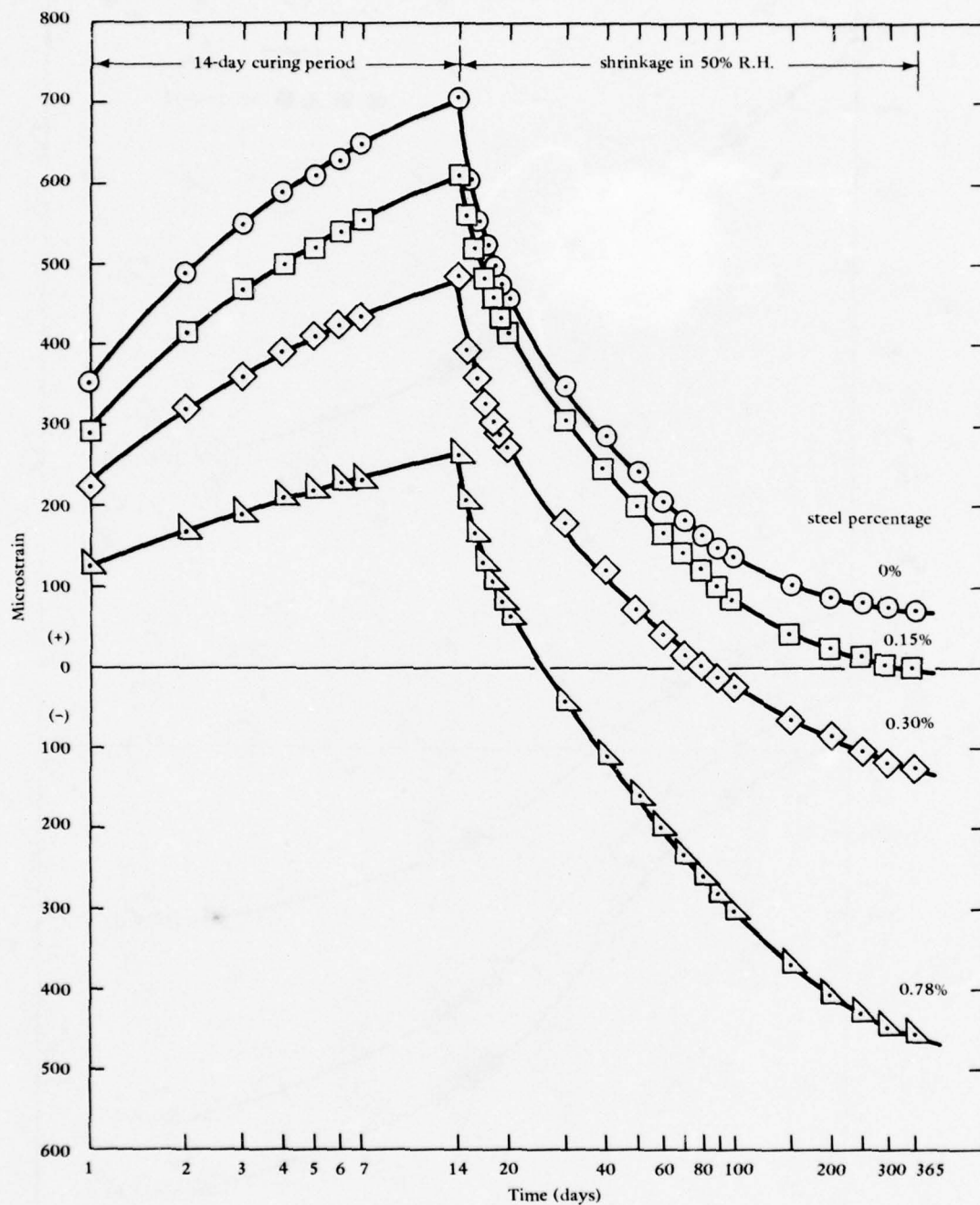


Figure 13. Strain in 4-in.-thick prisms of 7.5 SC concrete after 365 days in controlled environments.



(a) 50% R.H.

Figure 14. Expansion-shrinkage of 4-in.-thick prisms of 7.5 SC concrete.

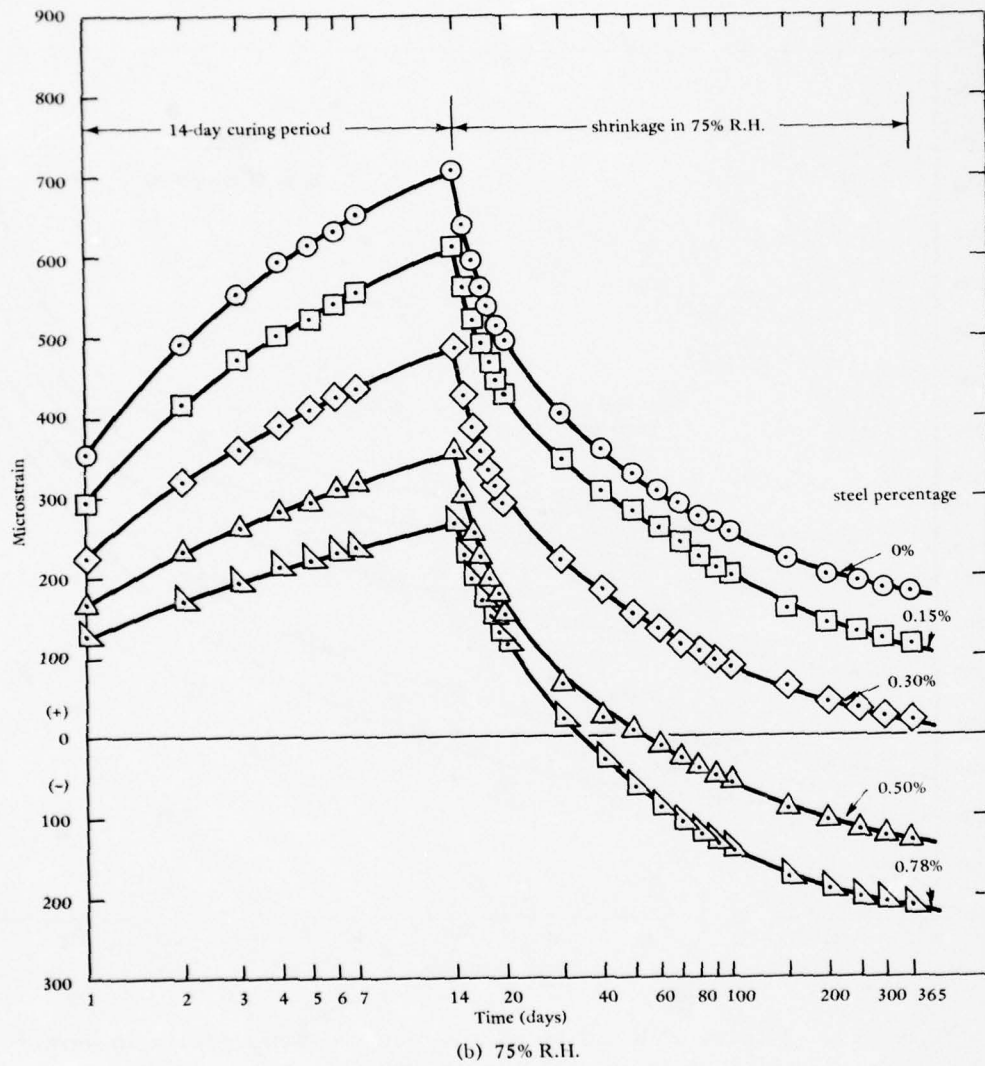


Figure 14. Continued



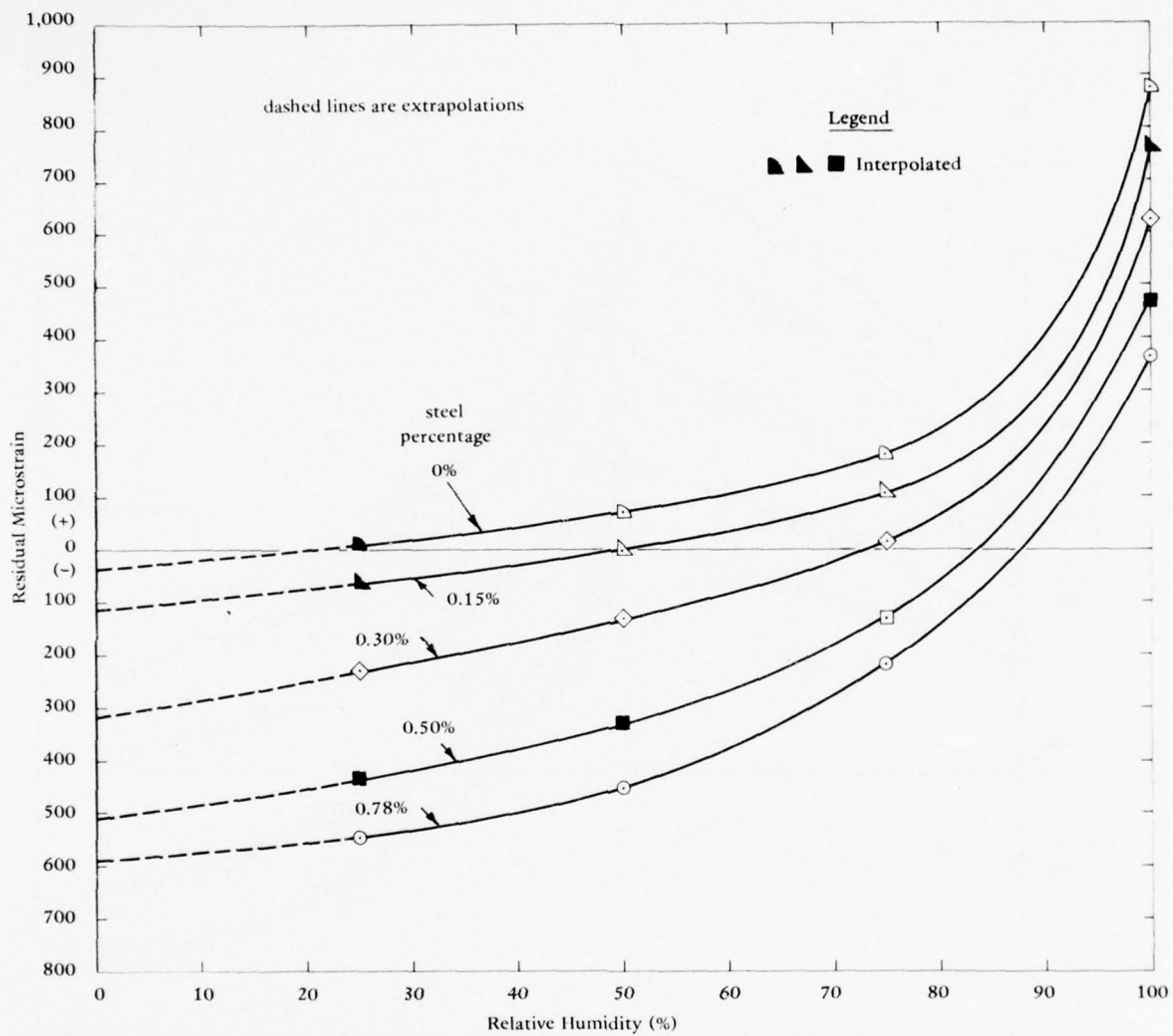
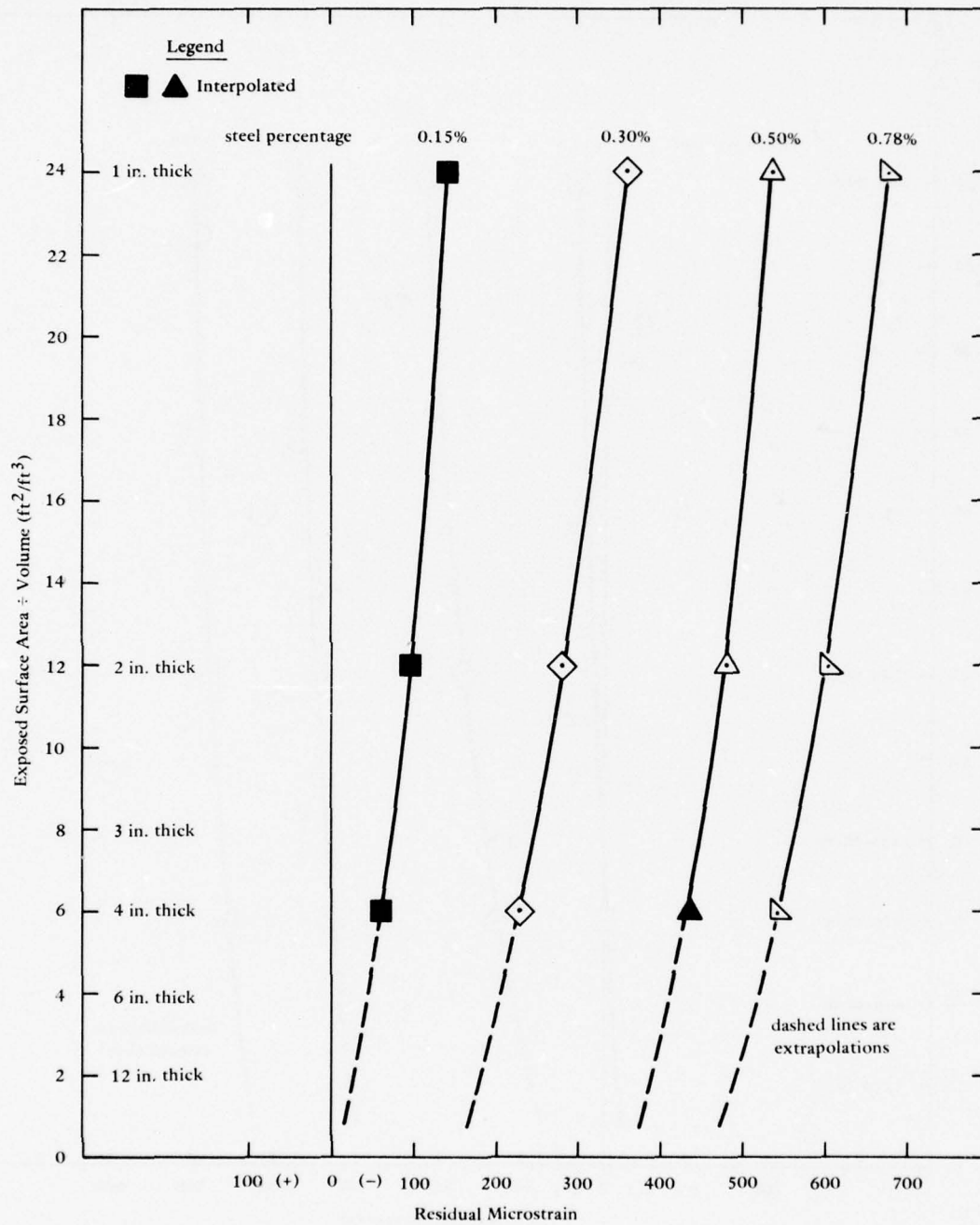
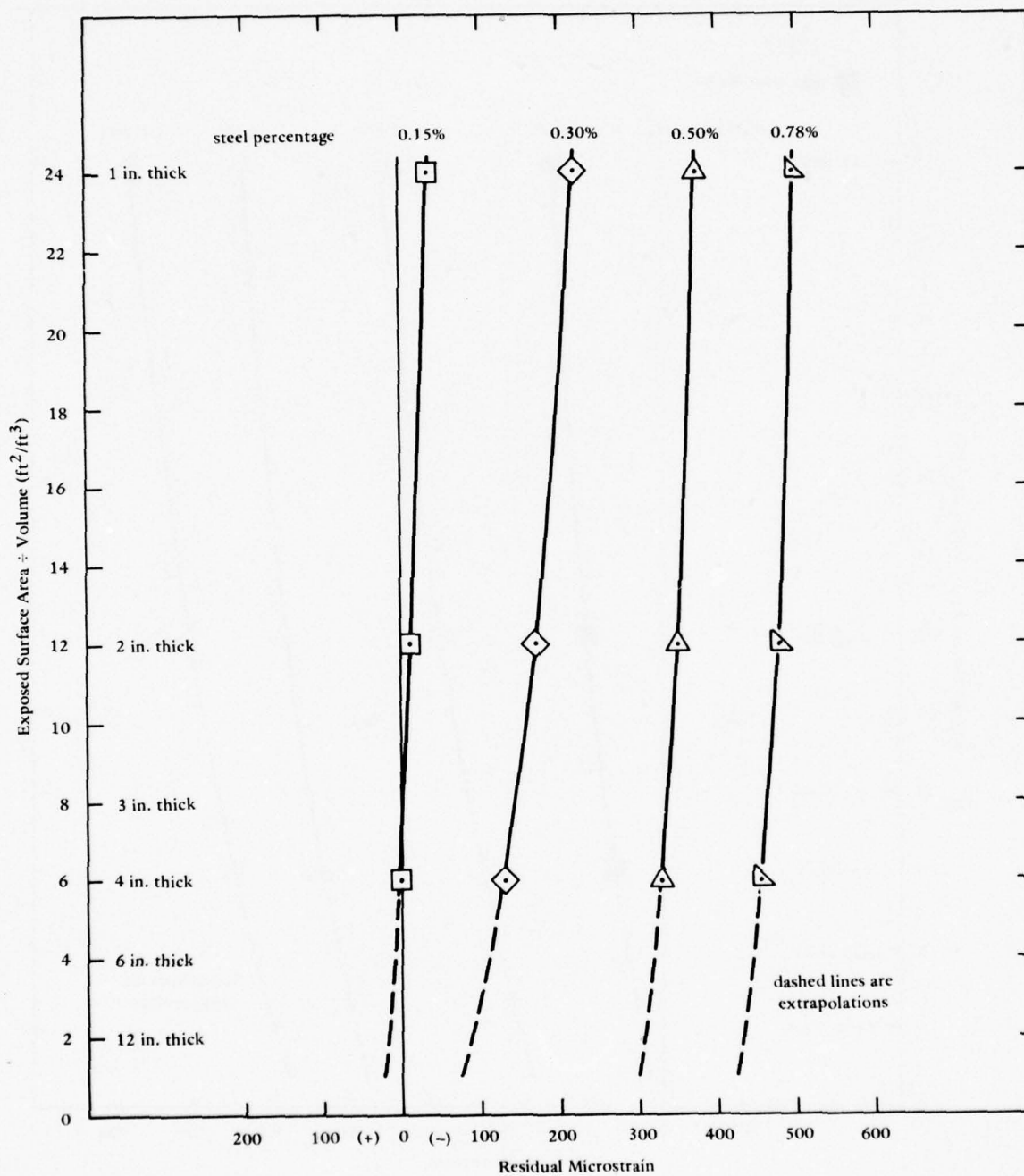


Figure 15. Effects of humidity upon 365-day residual strain in 4-in.-thick prisms of 7.5 SC concrete.



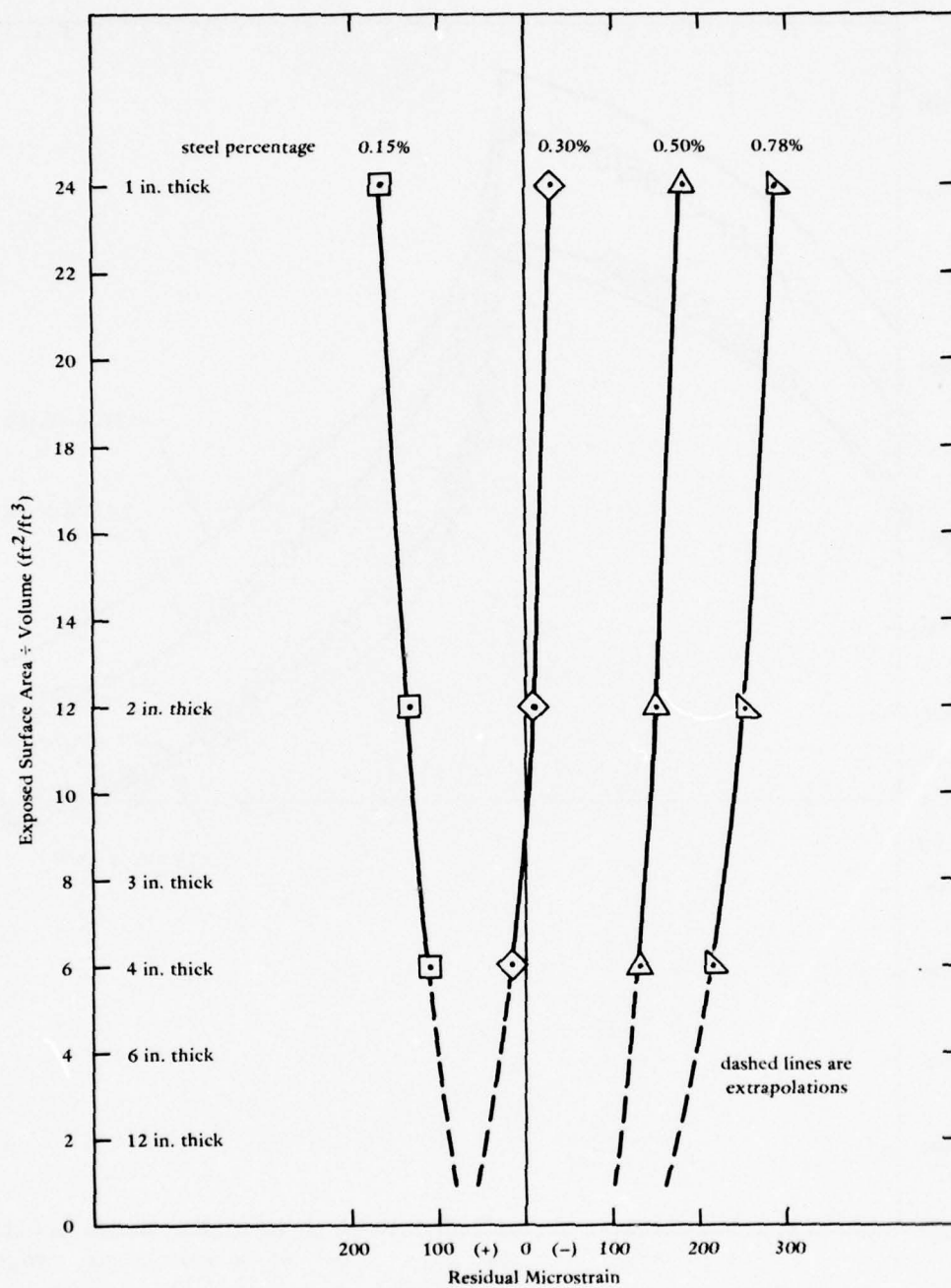
(a) 25% R.H.

Figure 16. Residual strain as a function of S/V for 7.5 SC concrete.



(b) 50% R.H.

Figure 16. Continued



(c) 75% R.H.

Figure 16. Continued



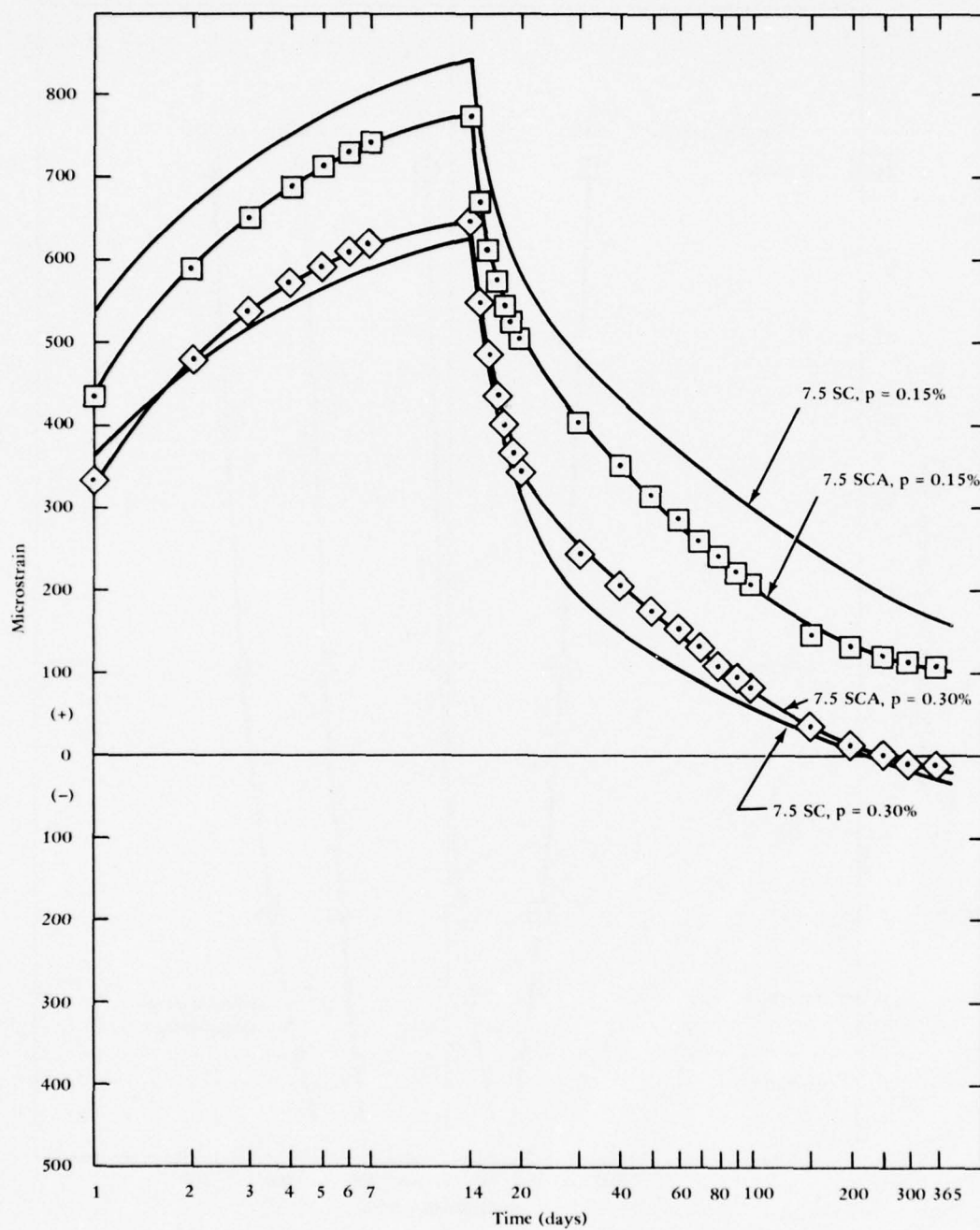


Figure 17. Comparison of 1-in.-thick prisms of 7.5 SC and 7.5 SCA concretes in 75% R.H.

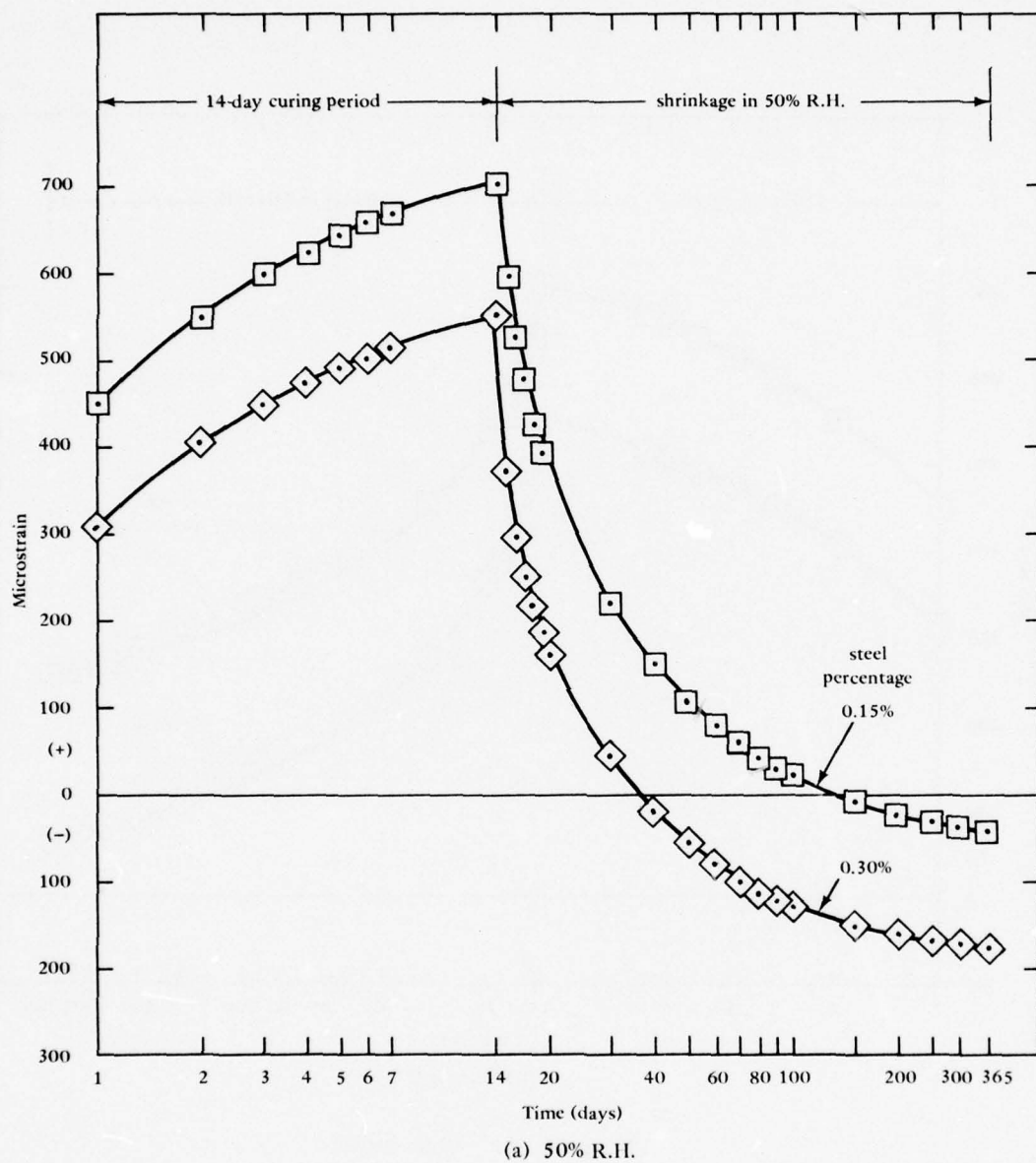


Figure 18. Expansion-shrinkage of 1-in.-thick prisms of 7.5 SC-L concrete.

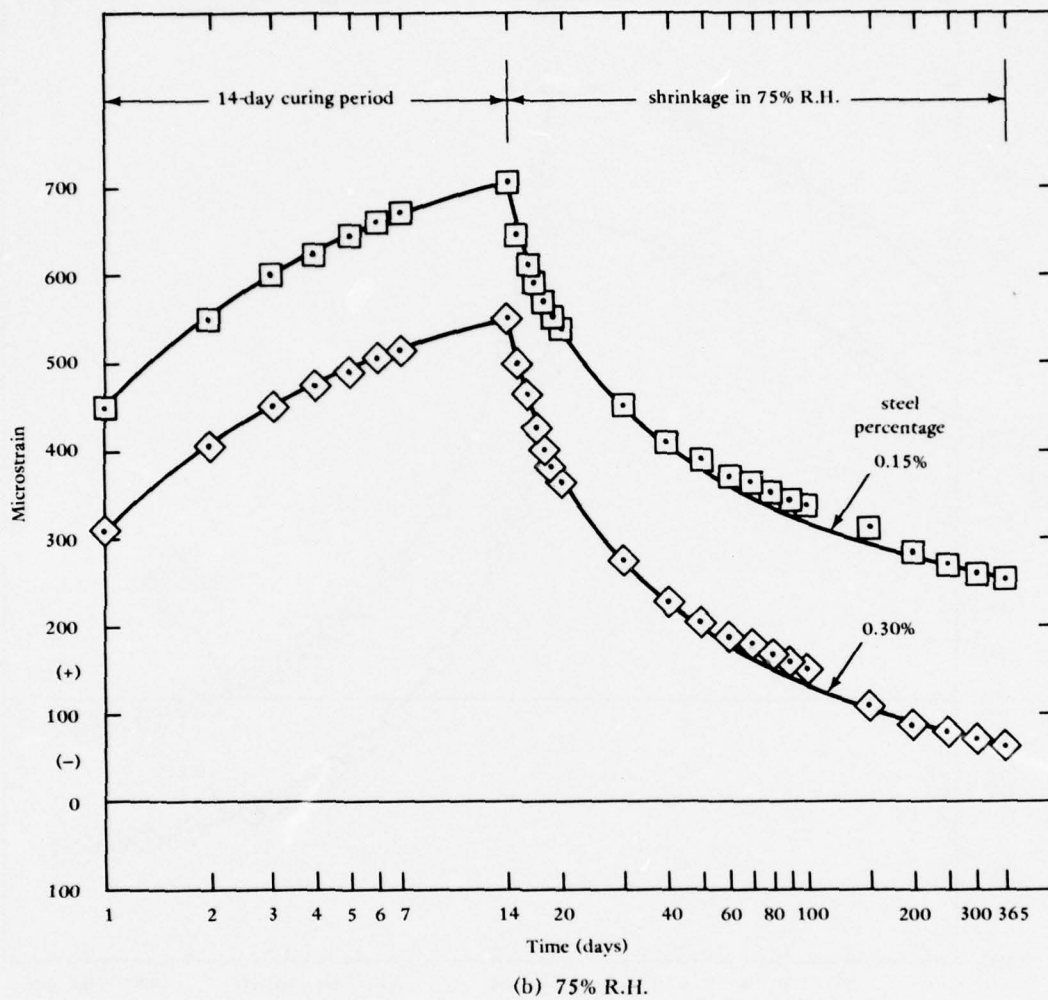
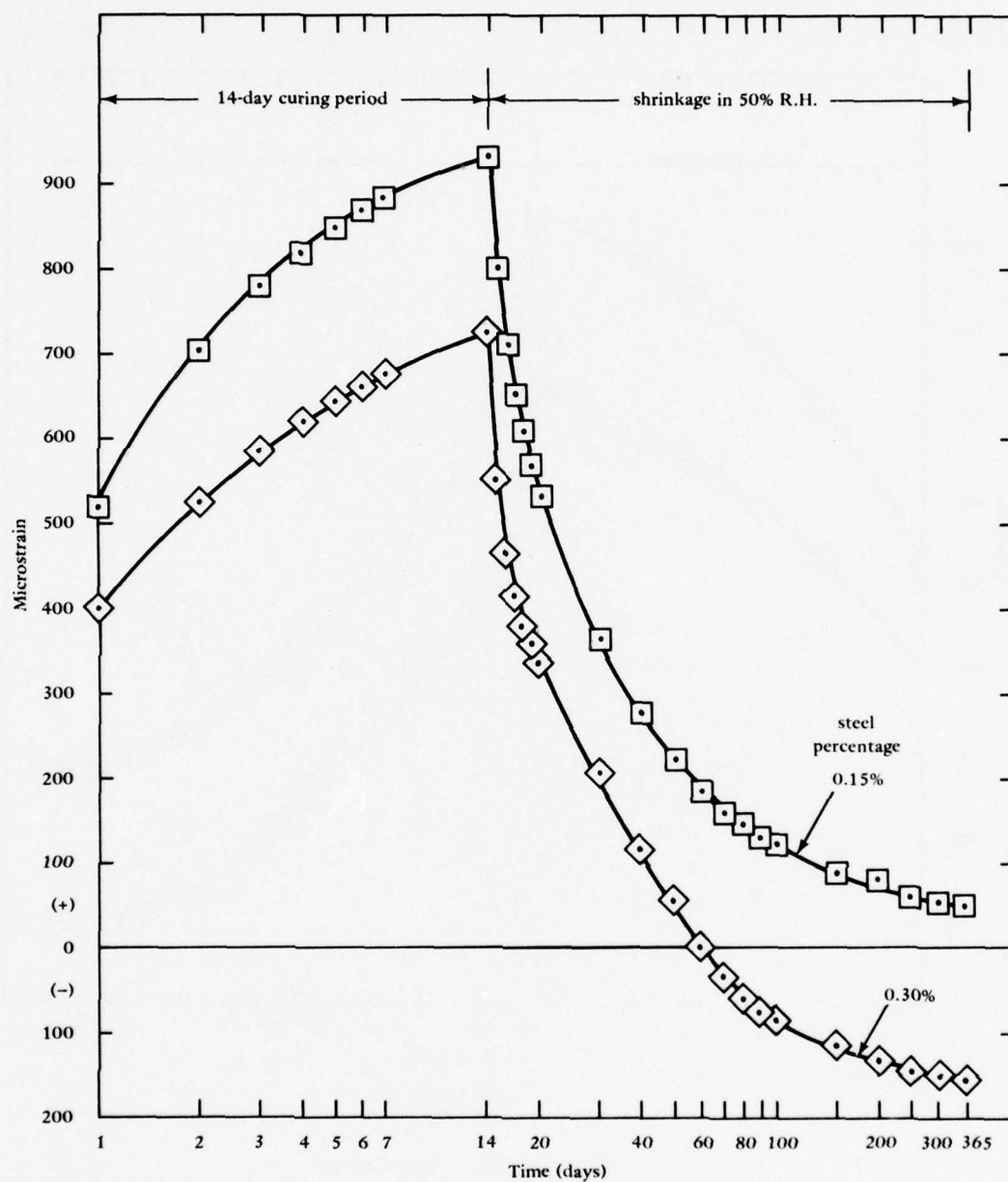


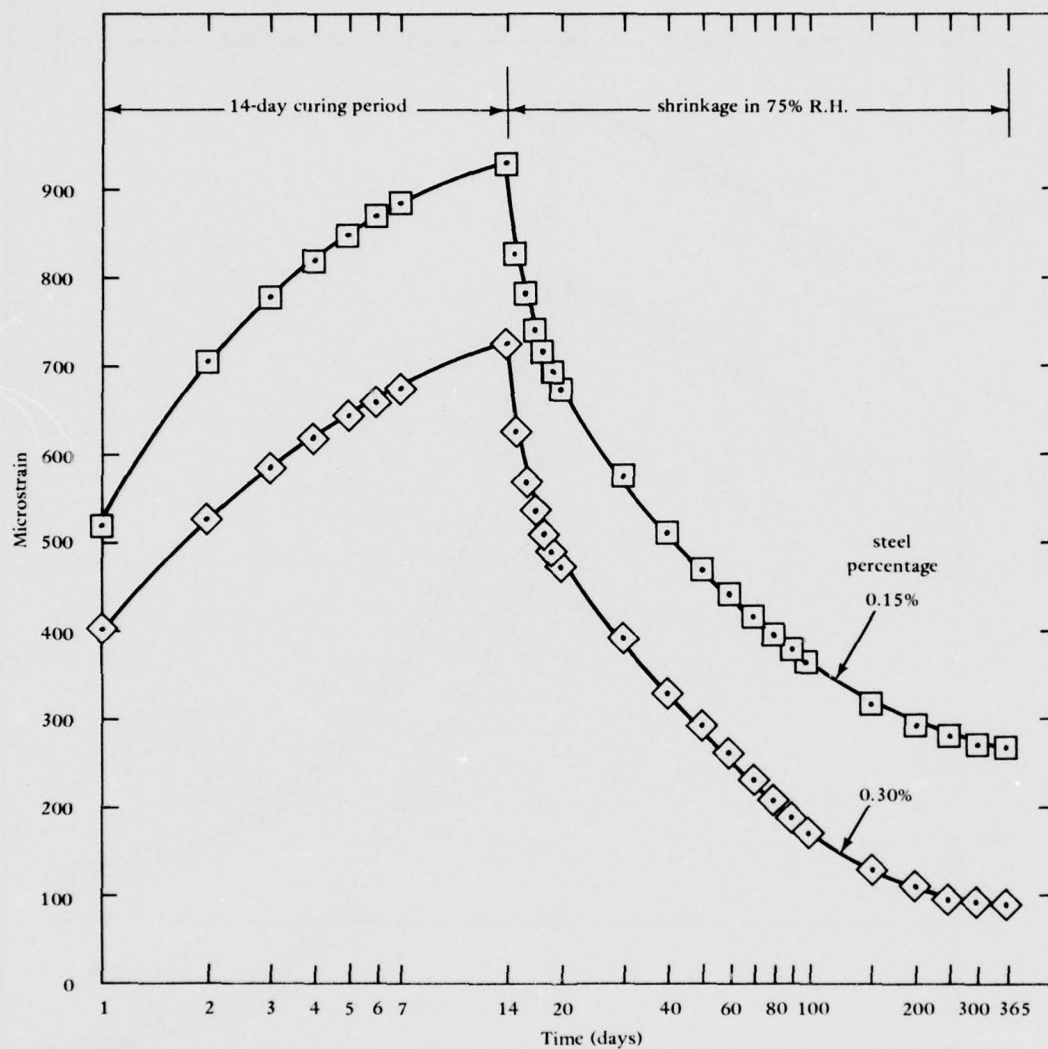
Figure 18. Continued



(a) 50% R.H.

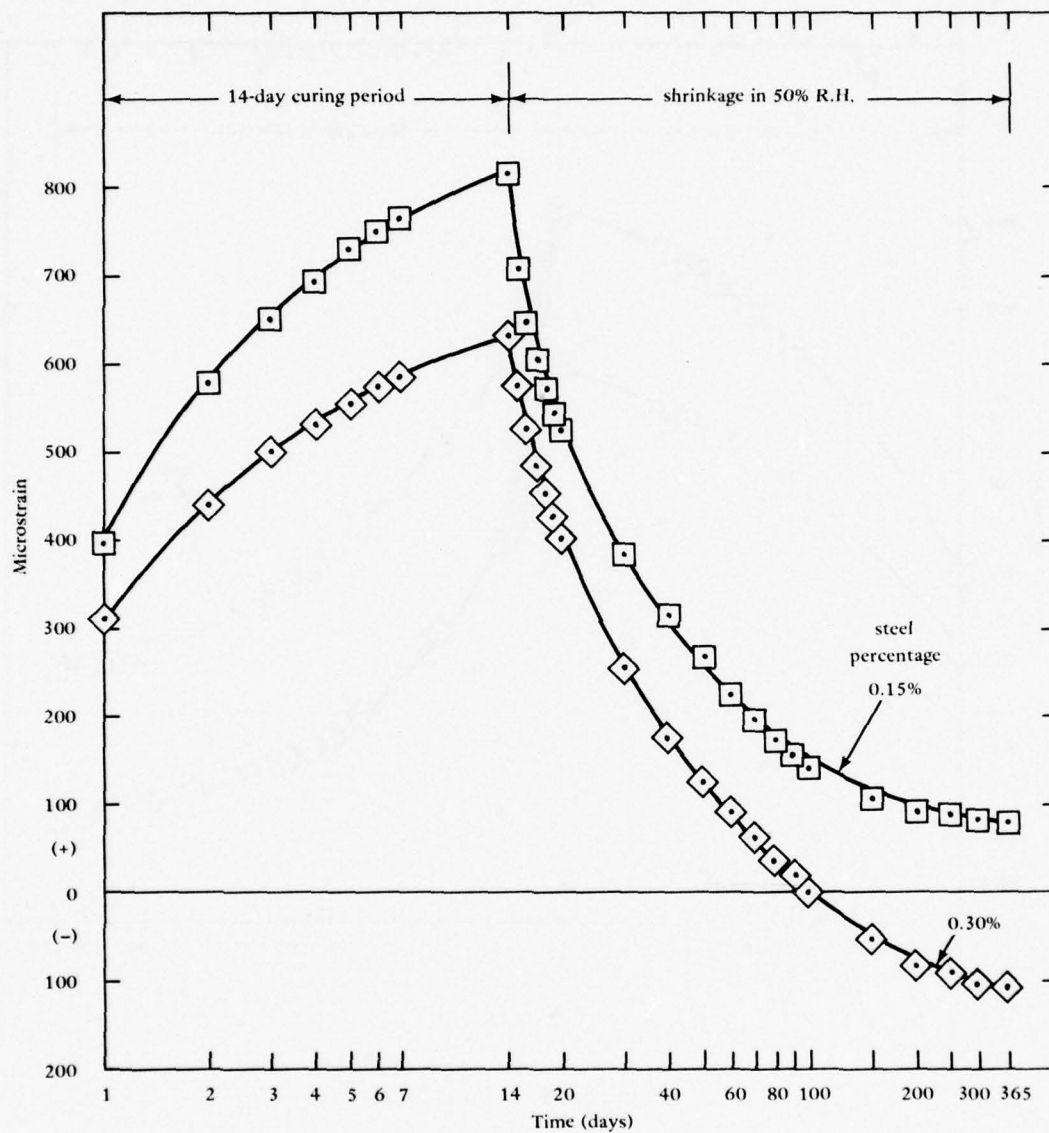
Figure 19. Expansion-shrinkage of 1-in.-thick prisms of 7.5 SCA-SLW concrete.





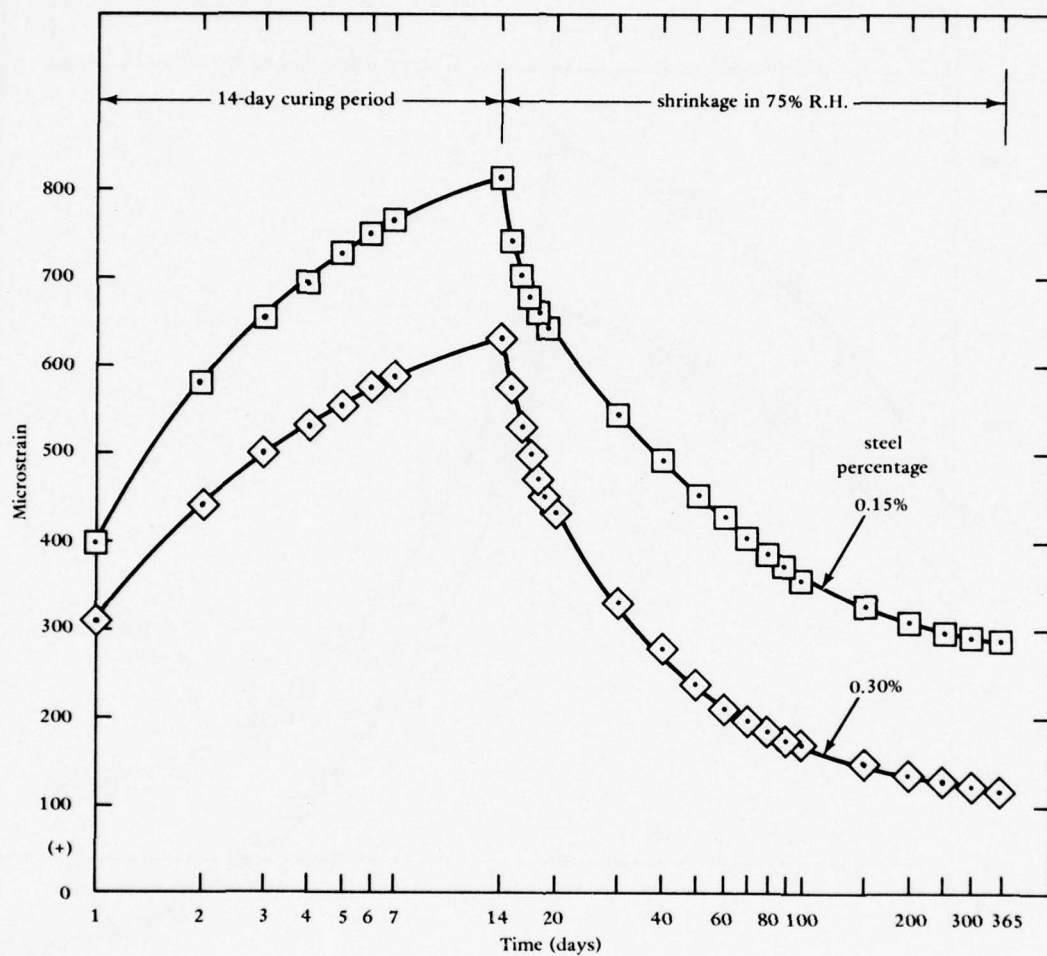
(b) 75% R.H.

Figure 19. Continued



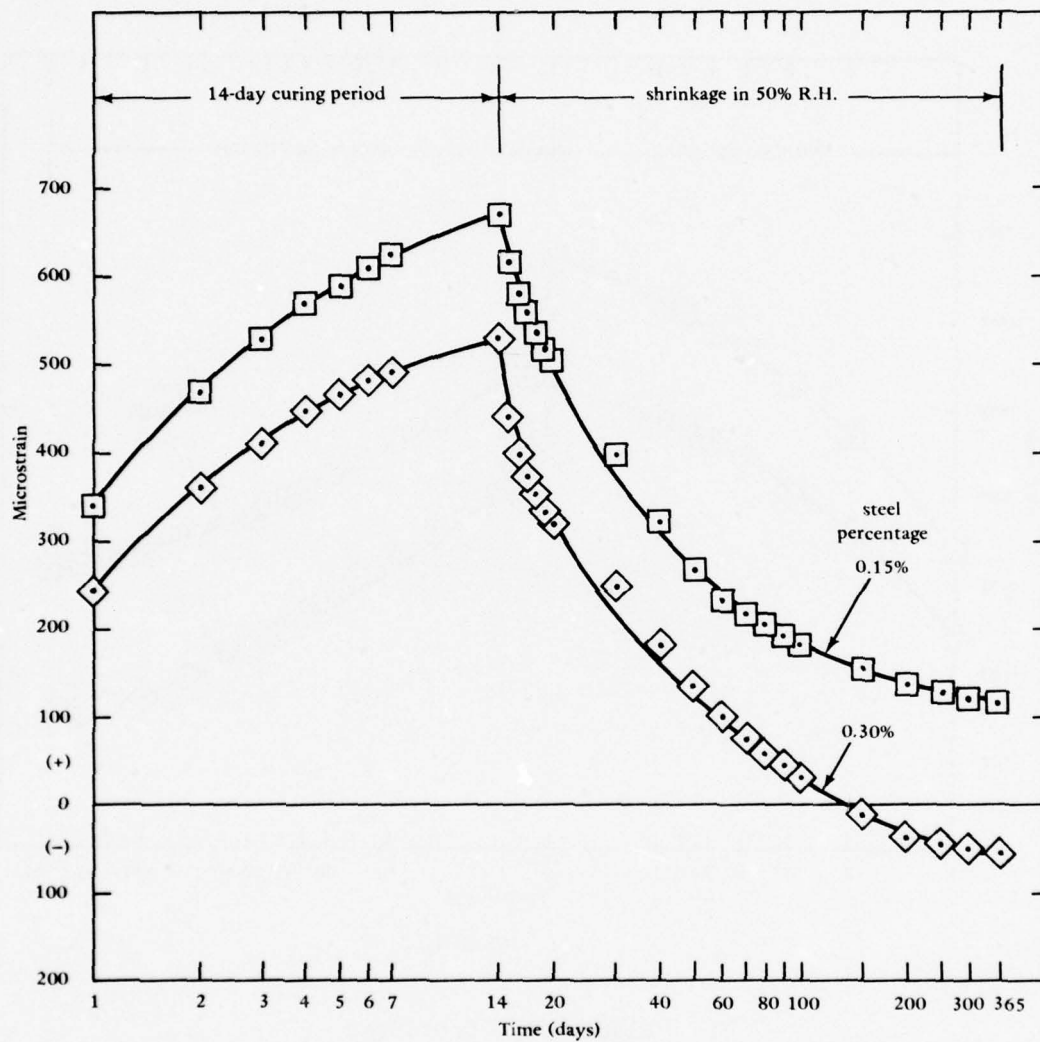
(a) 50% R.H.

Figure 20. Expansion-shrinkage of 2-in.-thick prisms of 7.5 SCA-SLW concrete.



(b) 75% R.H.

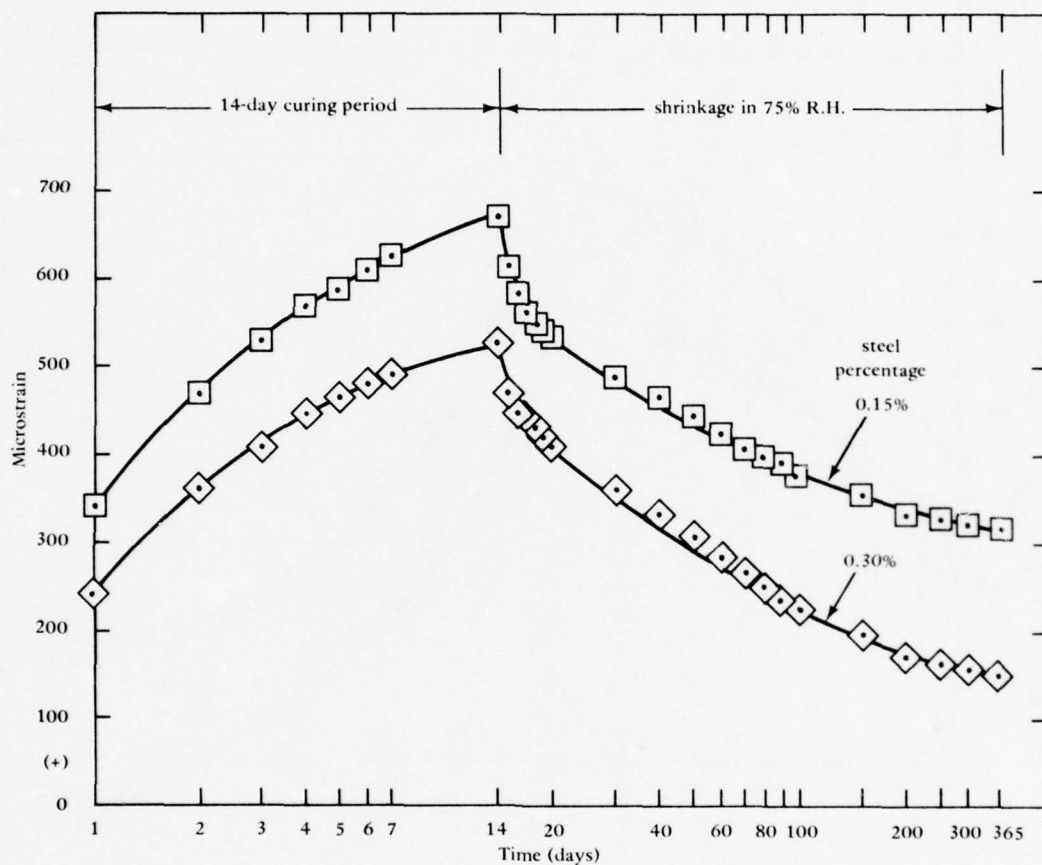
Figure 20. Continued



(a) 50% R.H.

Figure 21. Expansion-shrinkage of 4-in.-thick prisms of 7.5 SCA-SLW concrete.





(b) 75% R.H.

Figure 21. Continued

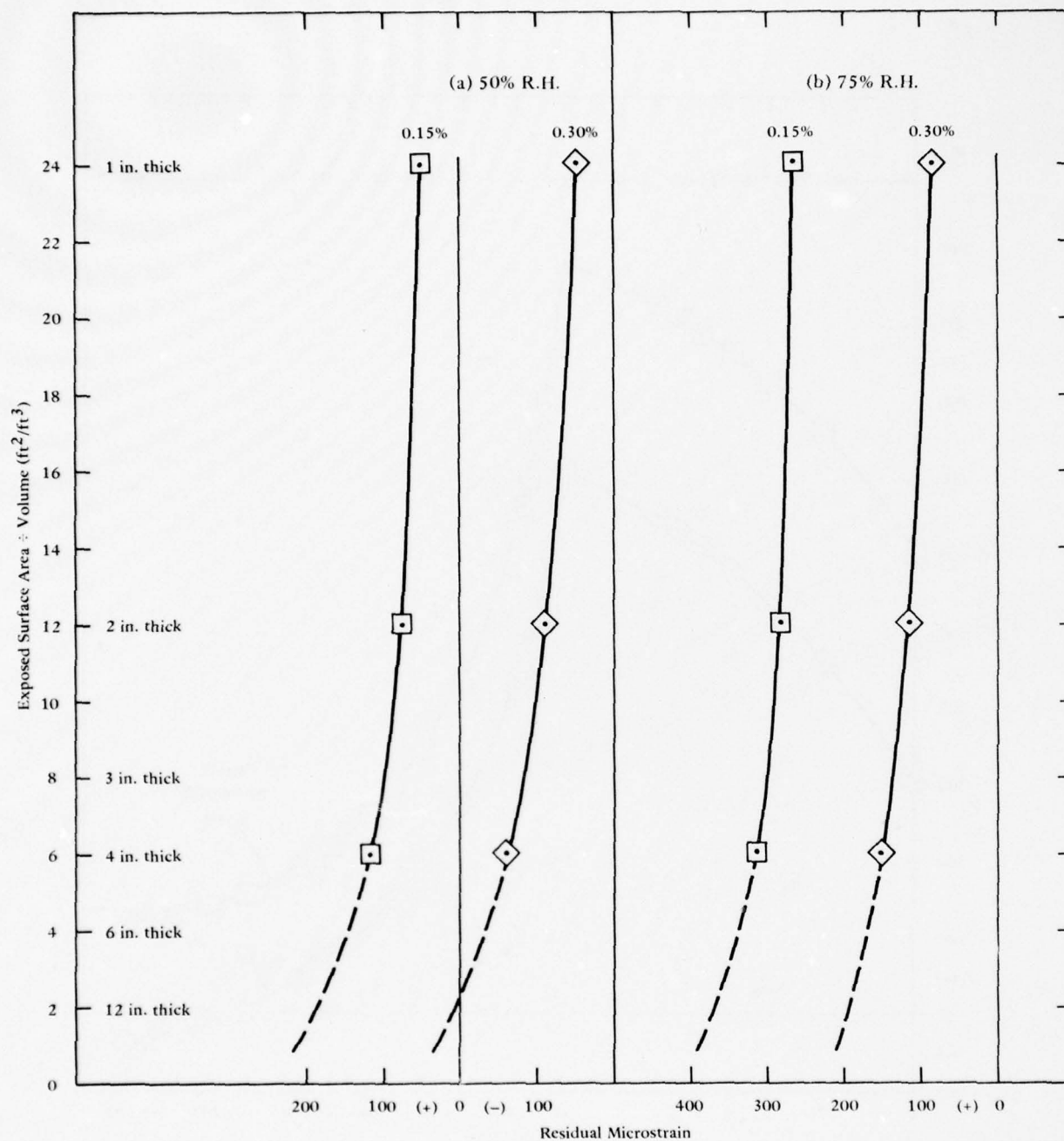
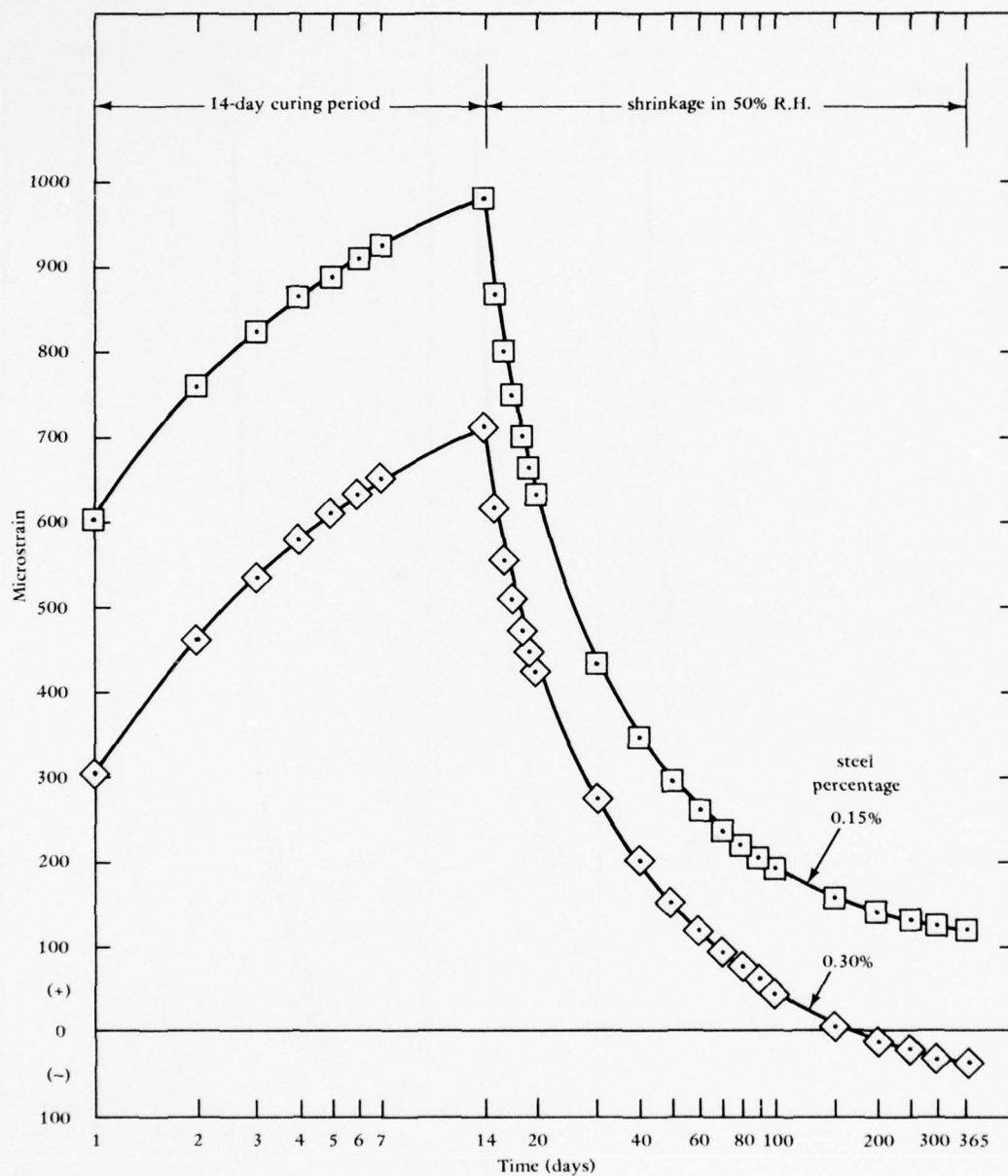
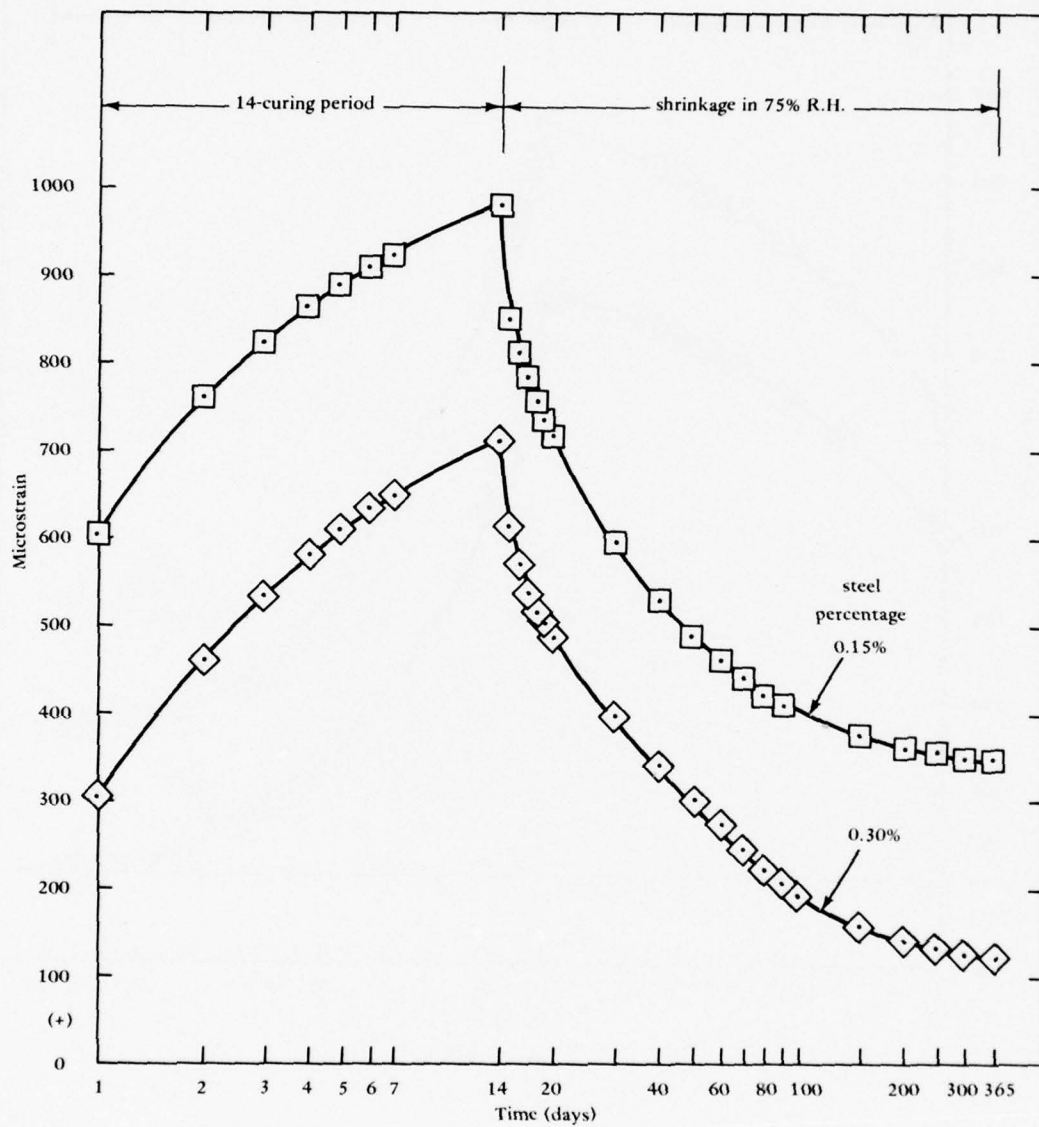


Figure 22. Residual strain after 365 days as a function of S/V for SCA-SLW concrete.



(a) 50% R.H.

Figure 23. Expansion-shrinkage of 1-in.-thick prisms of 7.5 SCA-LW concrete.



(b) 75% R.H.

Figure 23. Continued



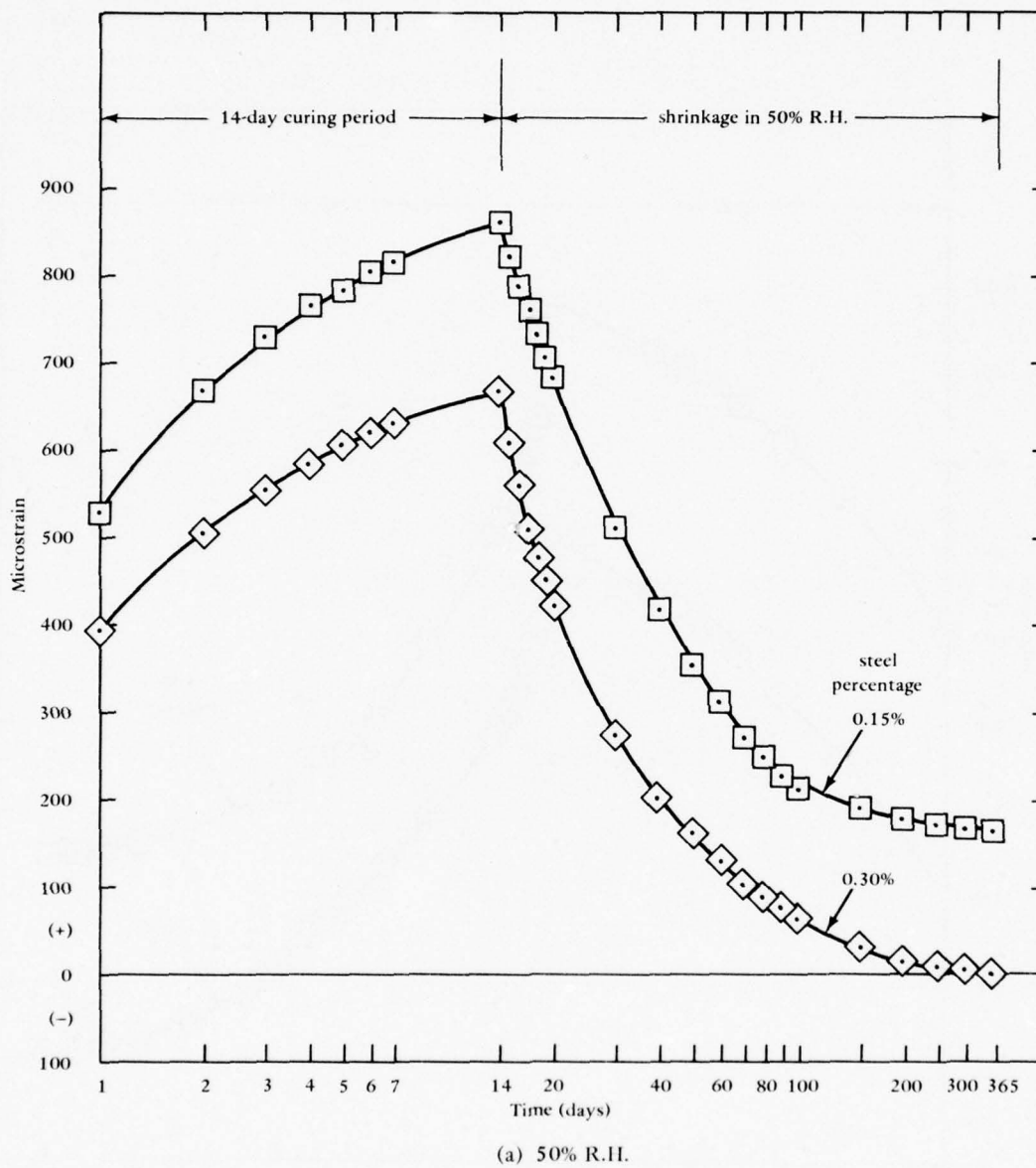
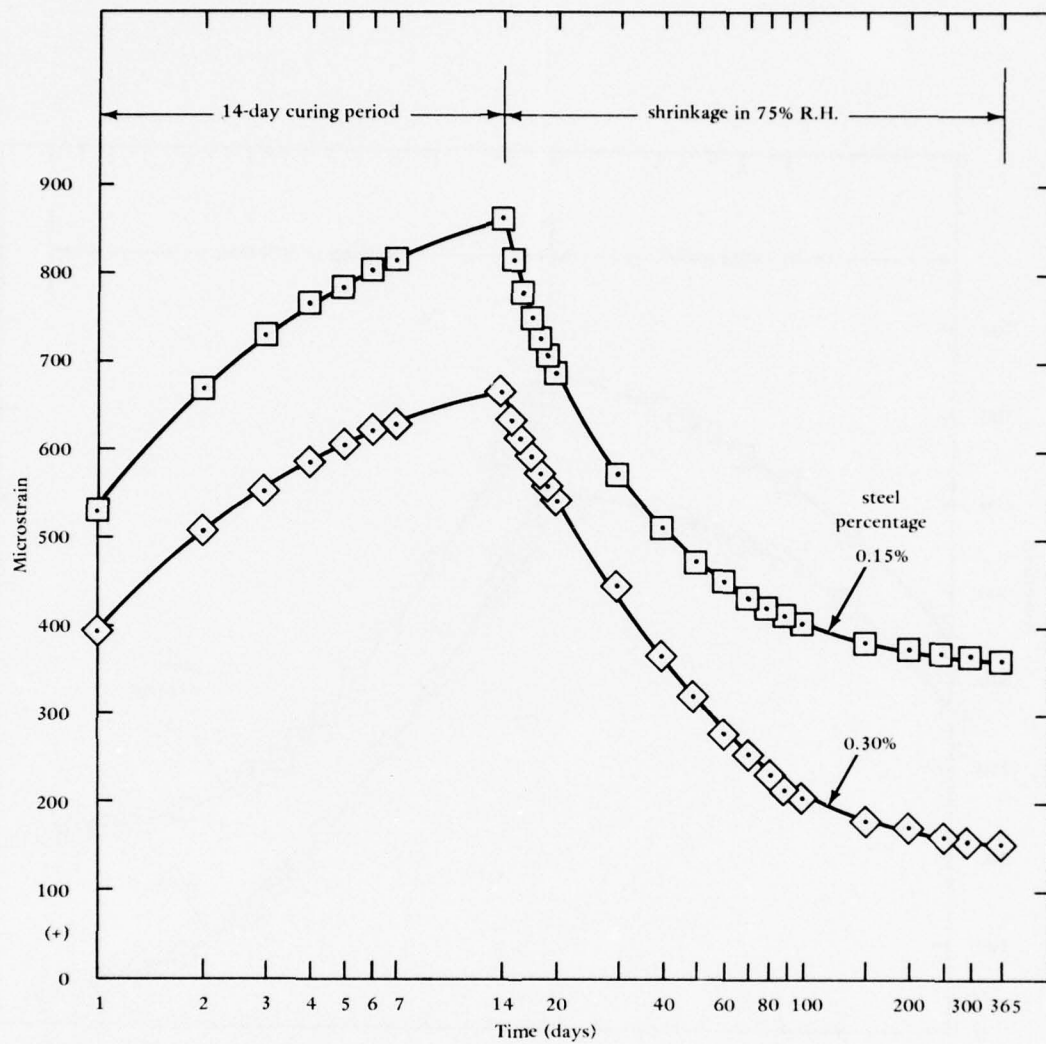
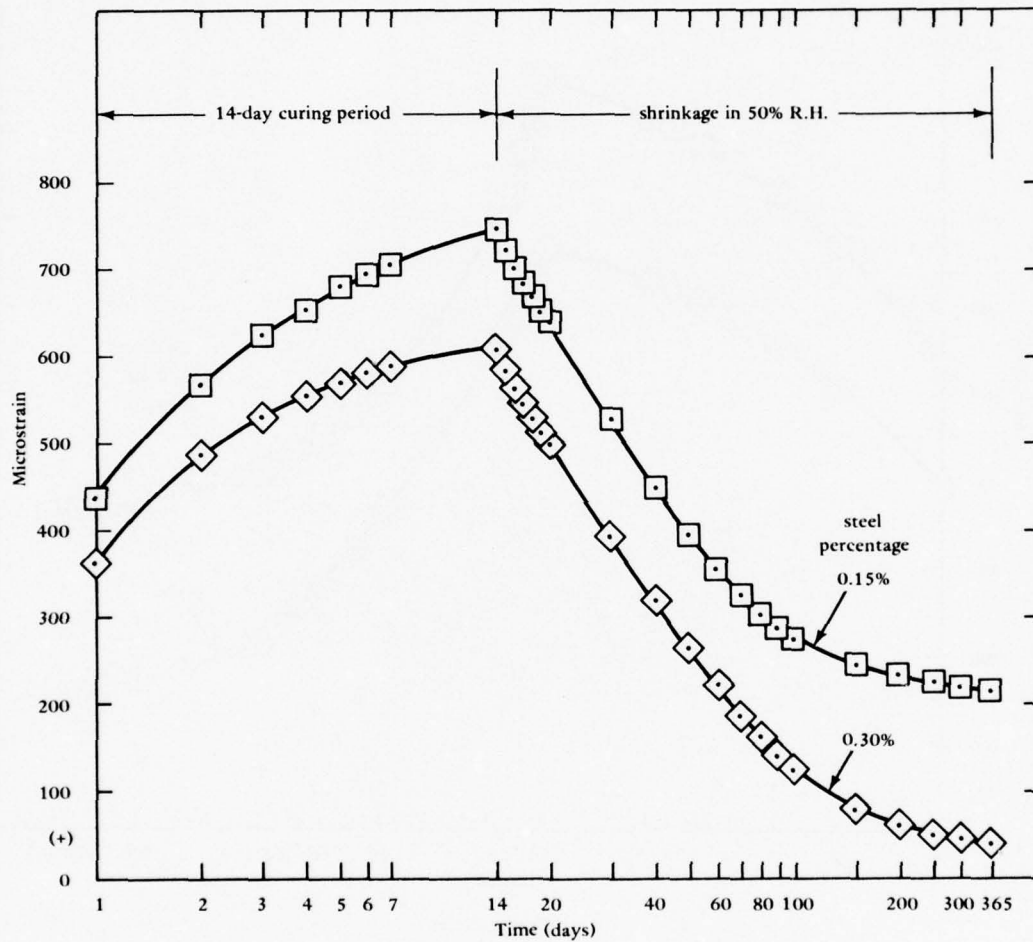


Figure 24. Expansion-shrinkage of 2-in.-thick prisms of 7.5 SCA-LW concrete.



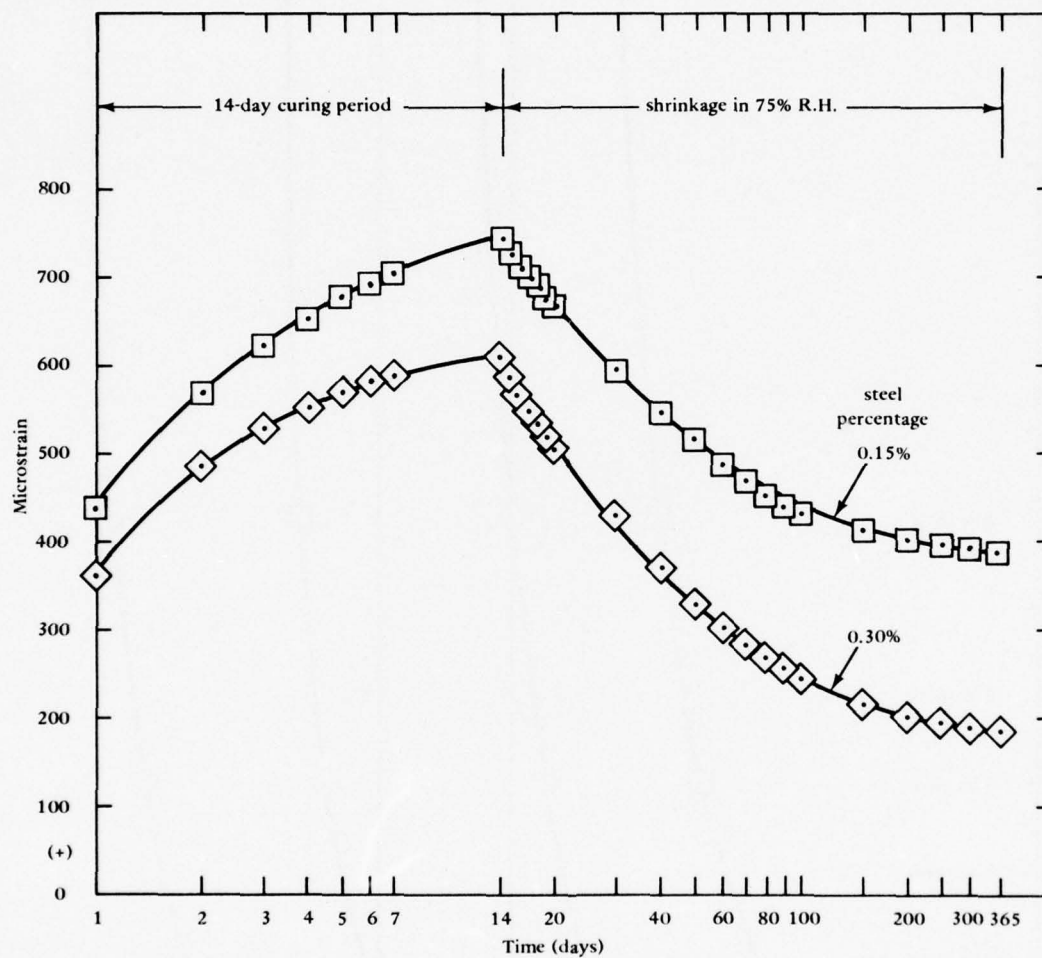
(b) 75% R.H.

Figure 24. Continued



(a) 50% R.H.

Figure 25. Expansion-shrinkage of 4-in.-thick prisms of 7.5 SCA-LW concrete.



(b) 75% R.H.

Figure 25. Continued



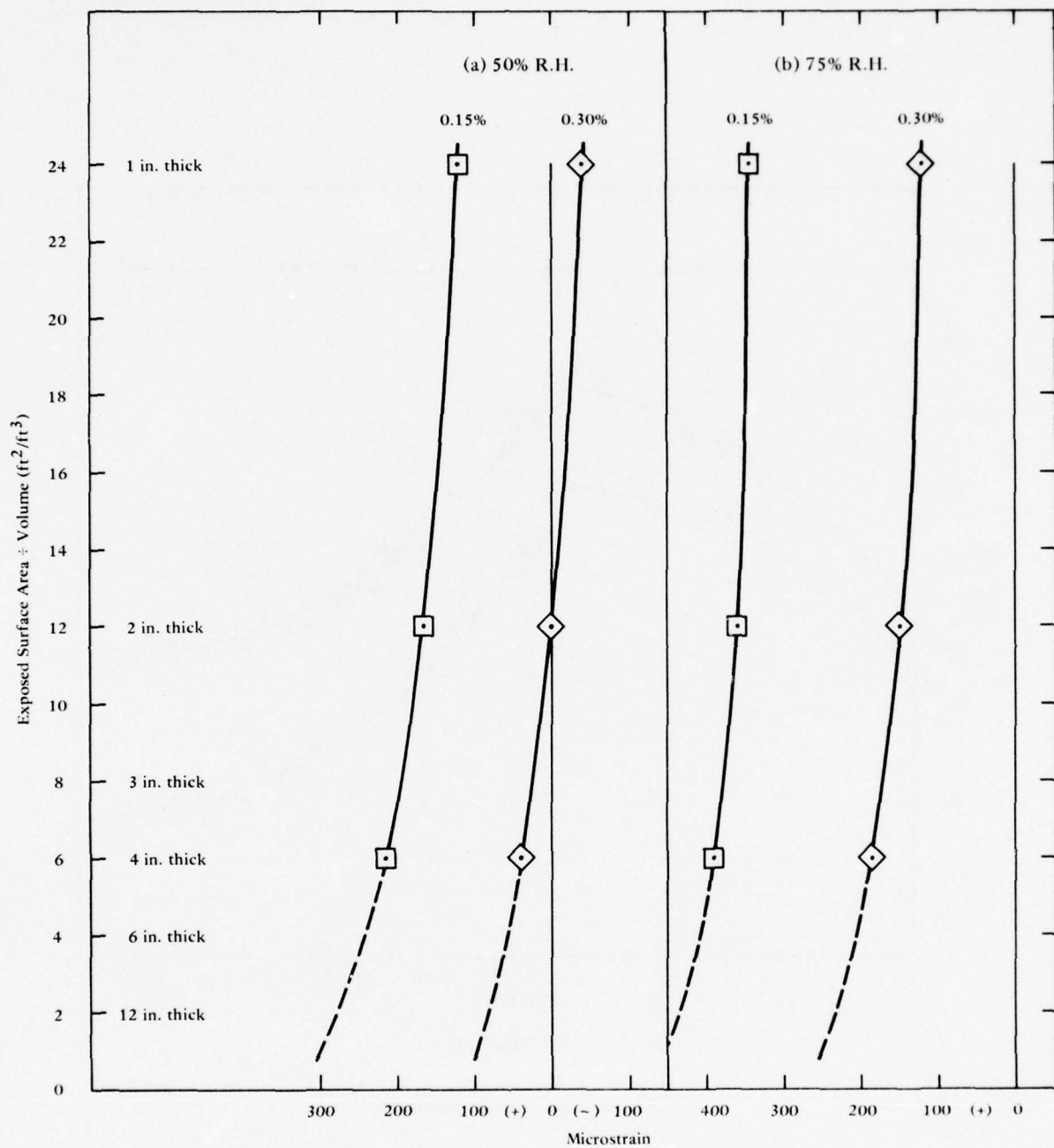
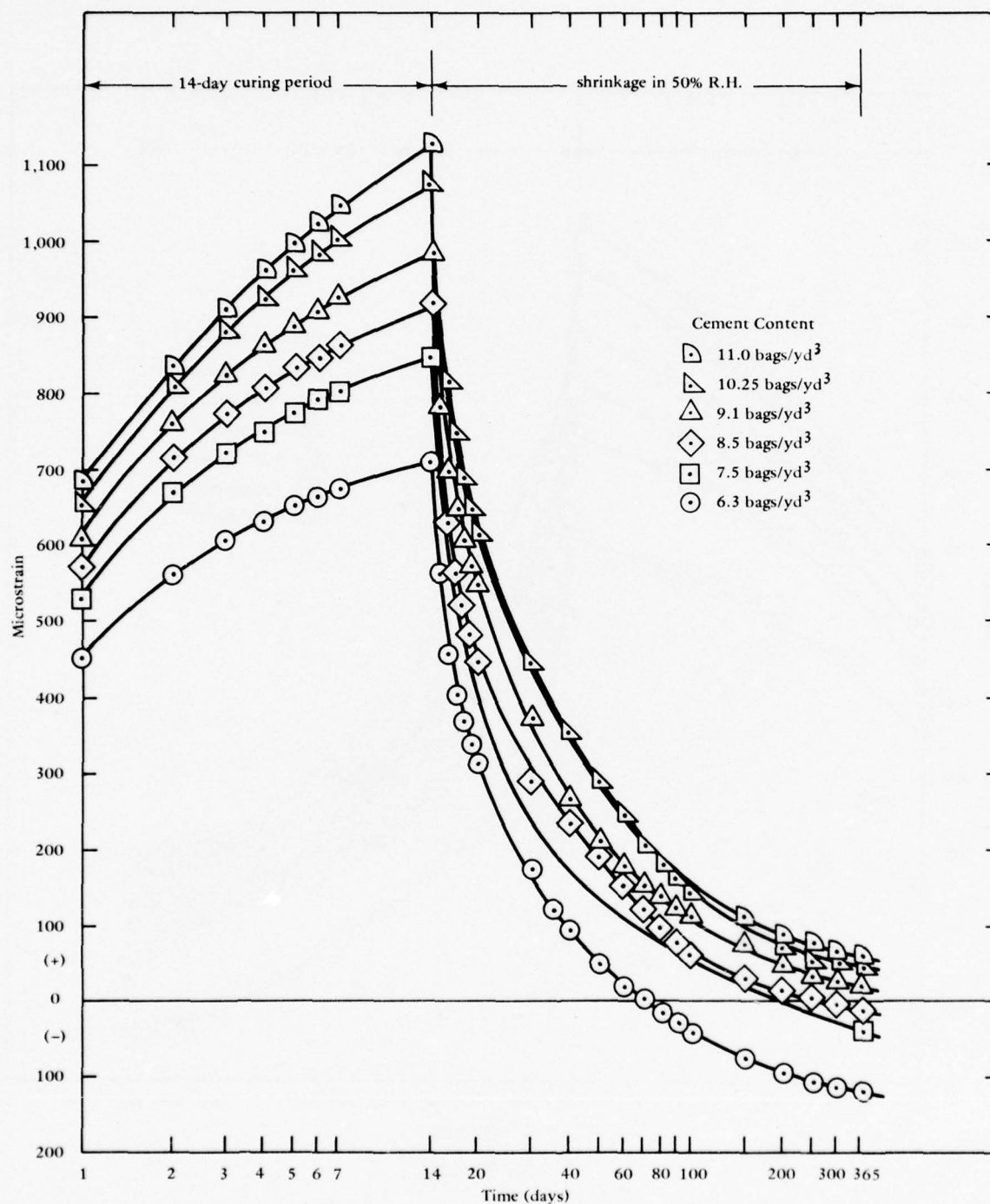
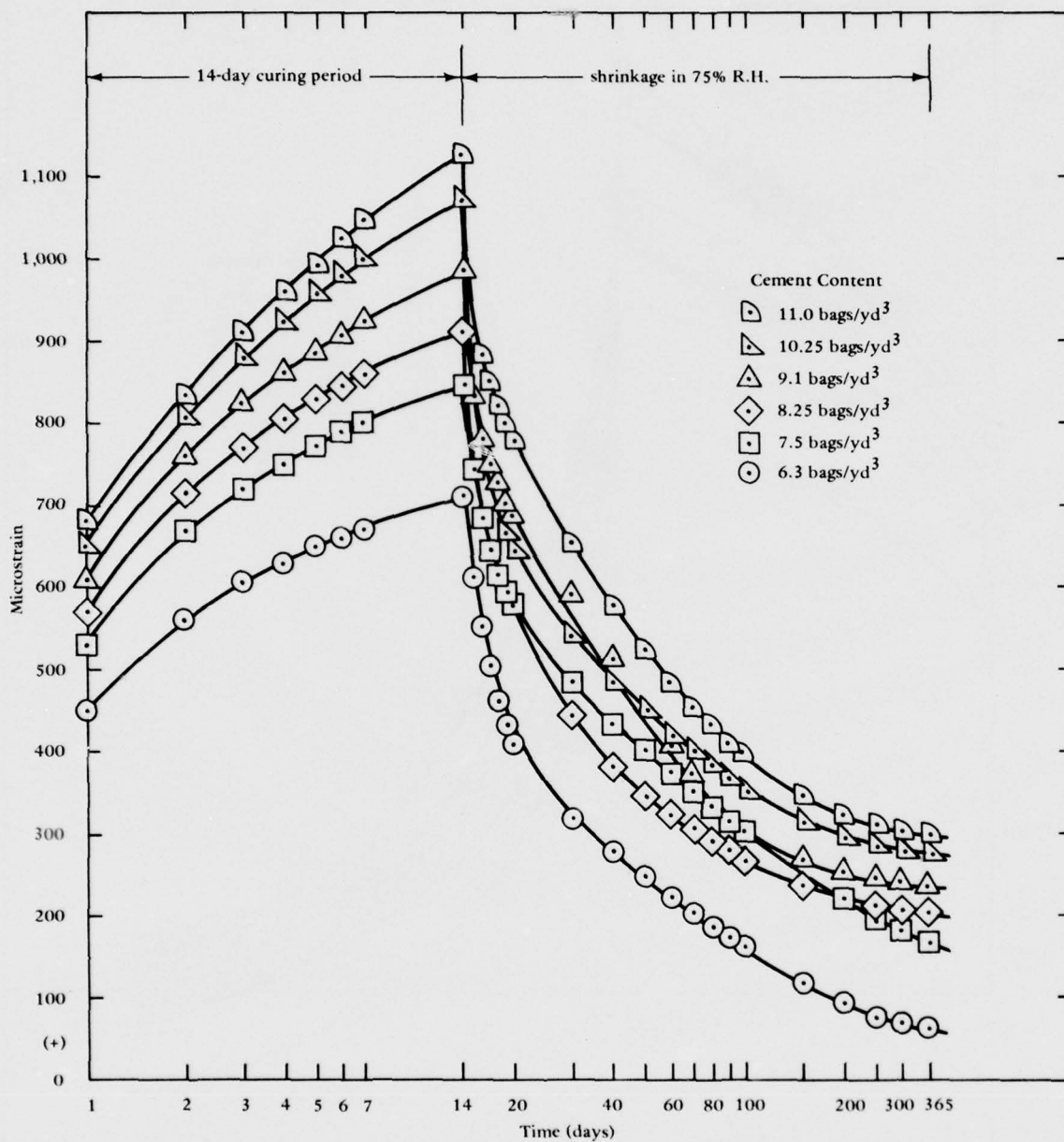


Figure 26. Residual strain after 365 days as a function of  $S/V$  for 7.5 SCA-LW concrete.



(a) 50% R.H.

Figure 27. Expansion-shrinkage of 1-in.-thick prisms of SC mixes with different cement contents.



(b) 75% R.H.

Figure 27. Continued

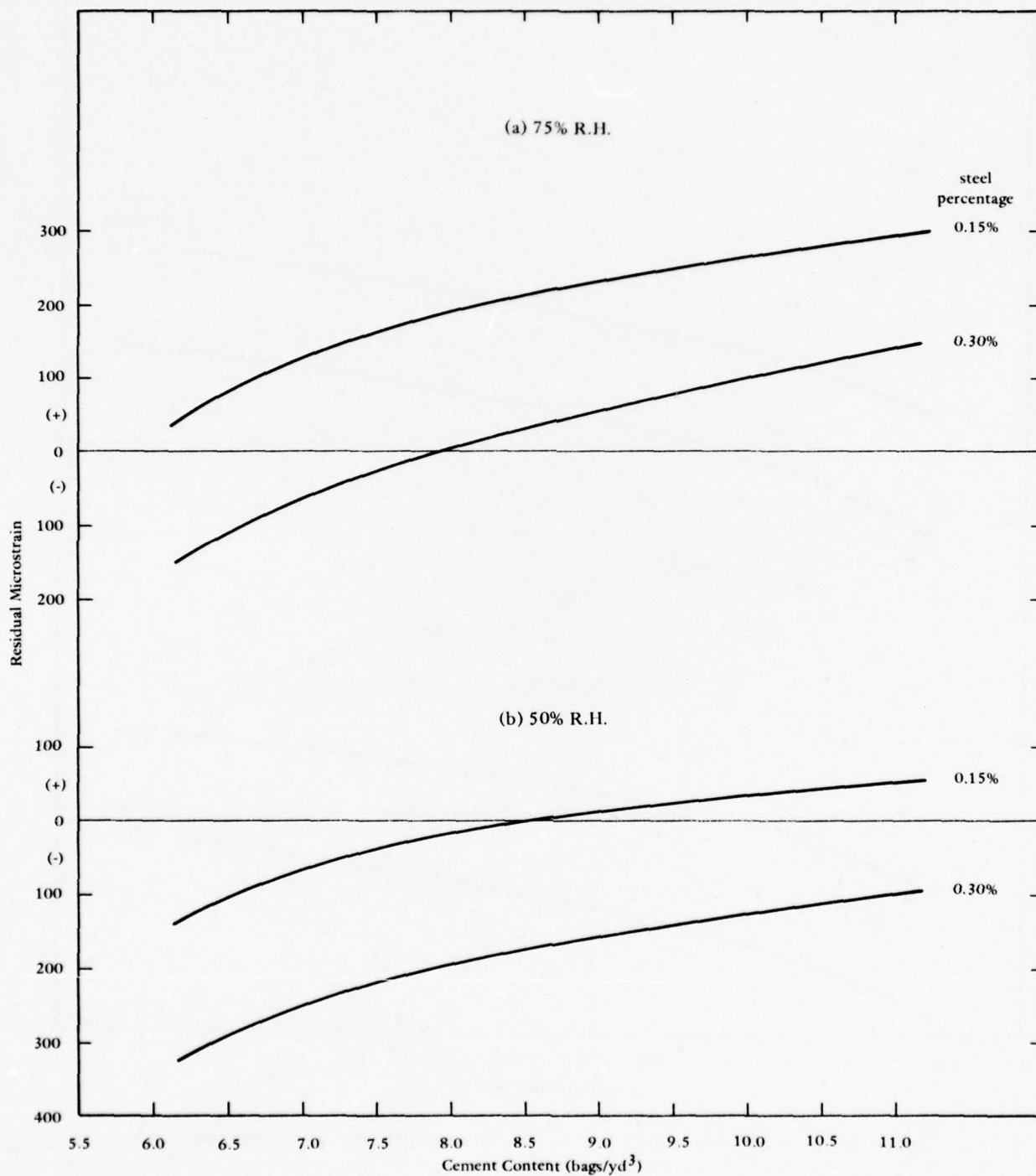


Figure 28. Residual strains after 365 days in 1-in.-thick prisms of SC mixes with different cement contents.



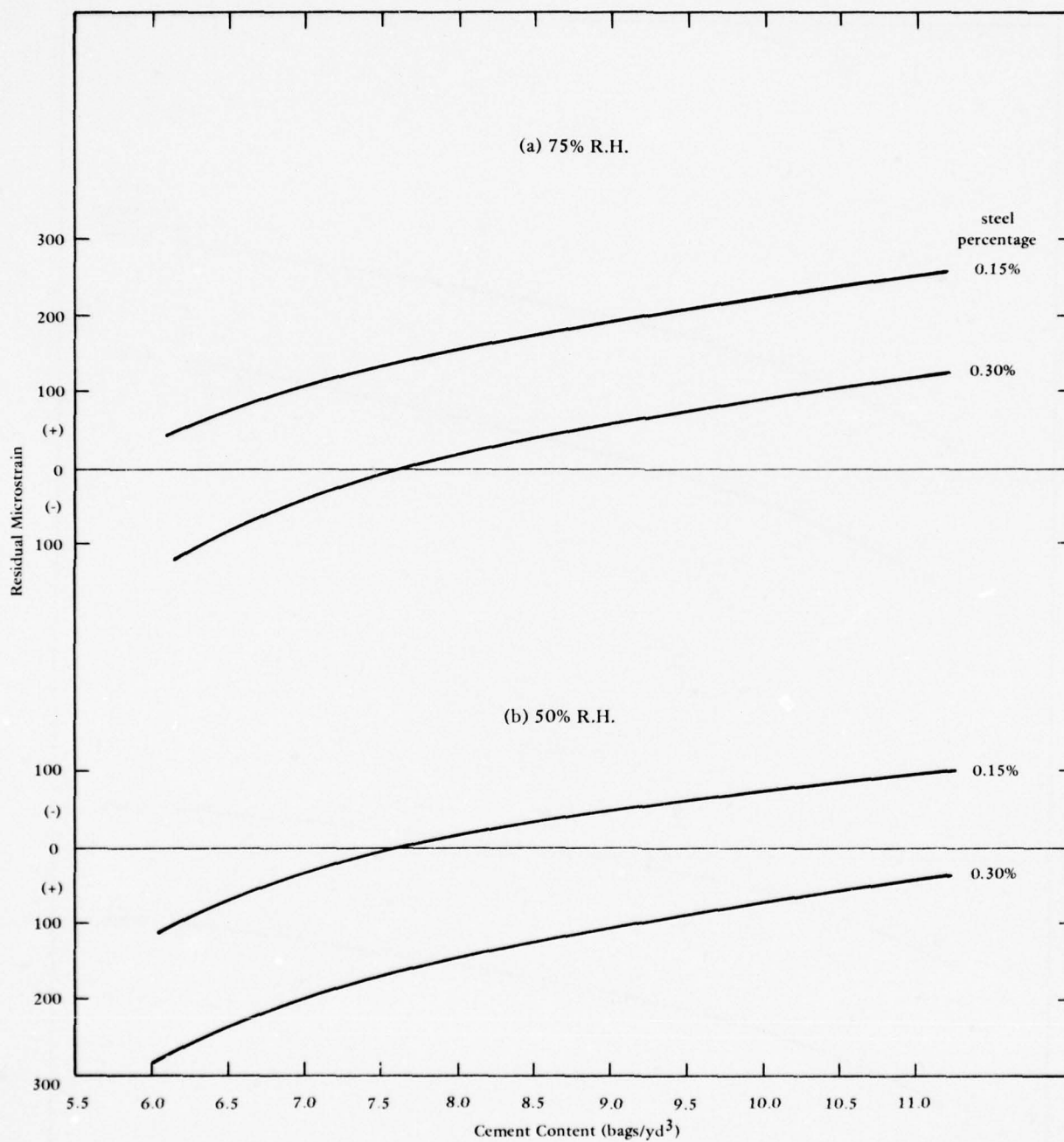
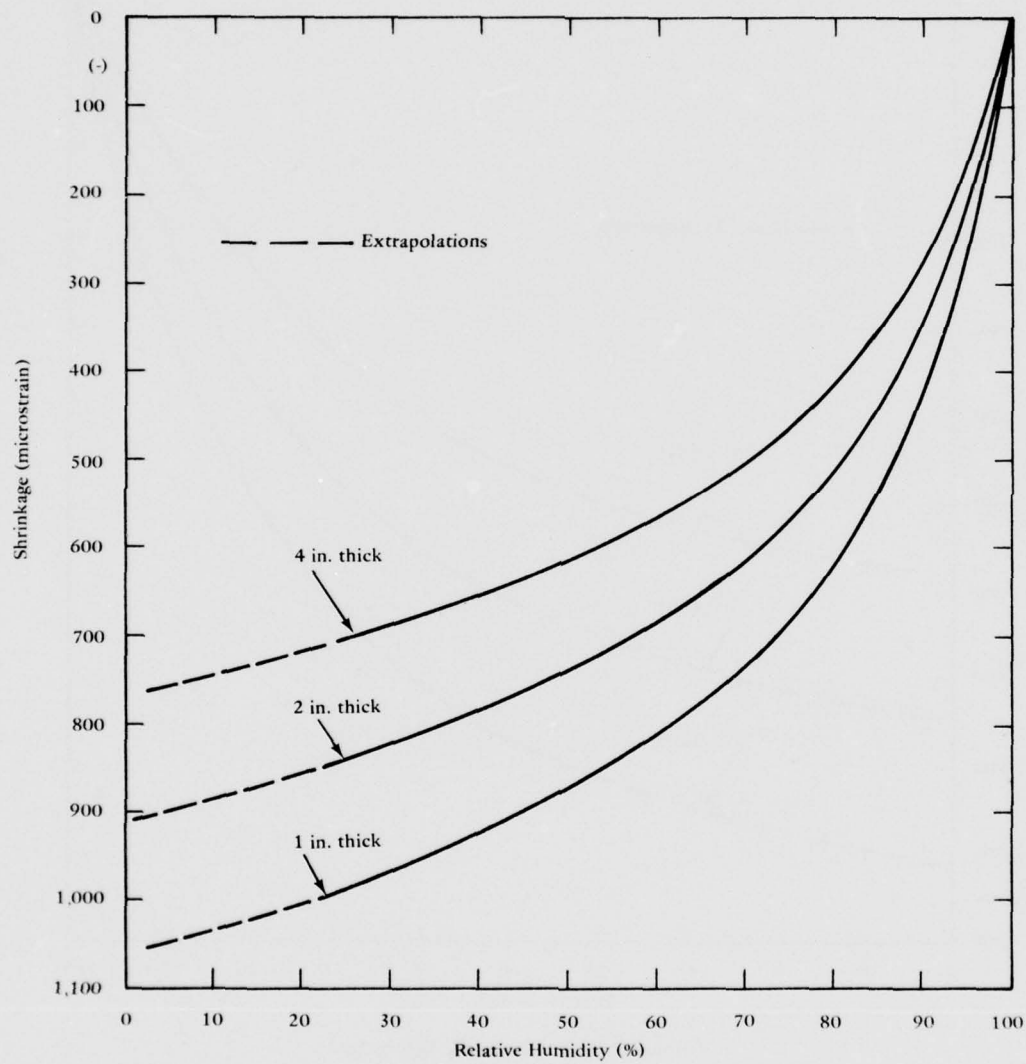
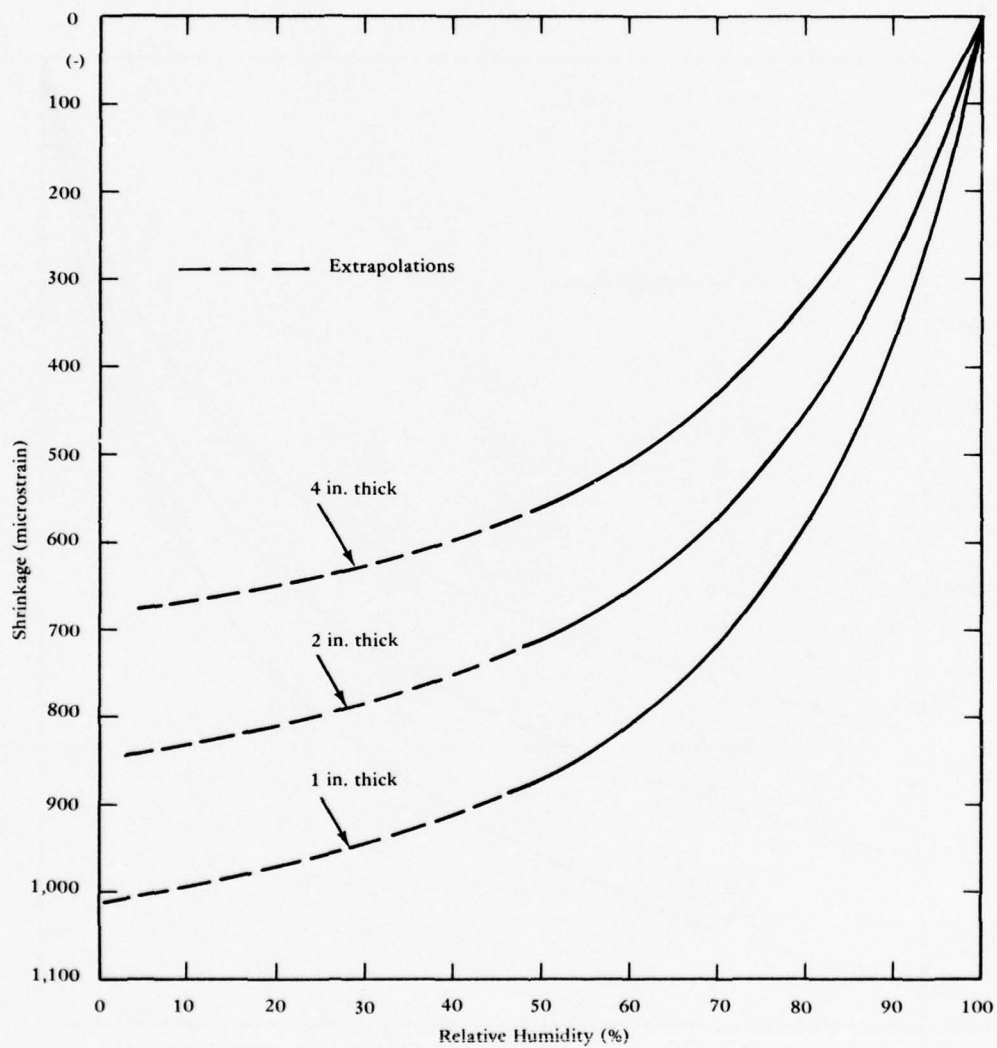


Figure 29. Residual strain in 2-in.-thick prisms of SC mixes with different cement contents.



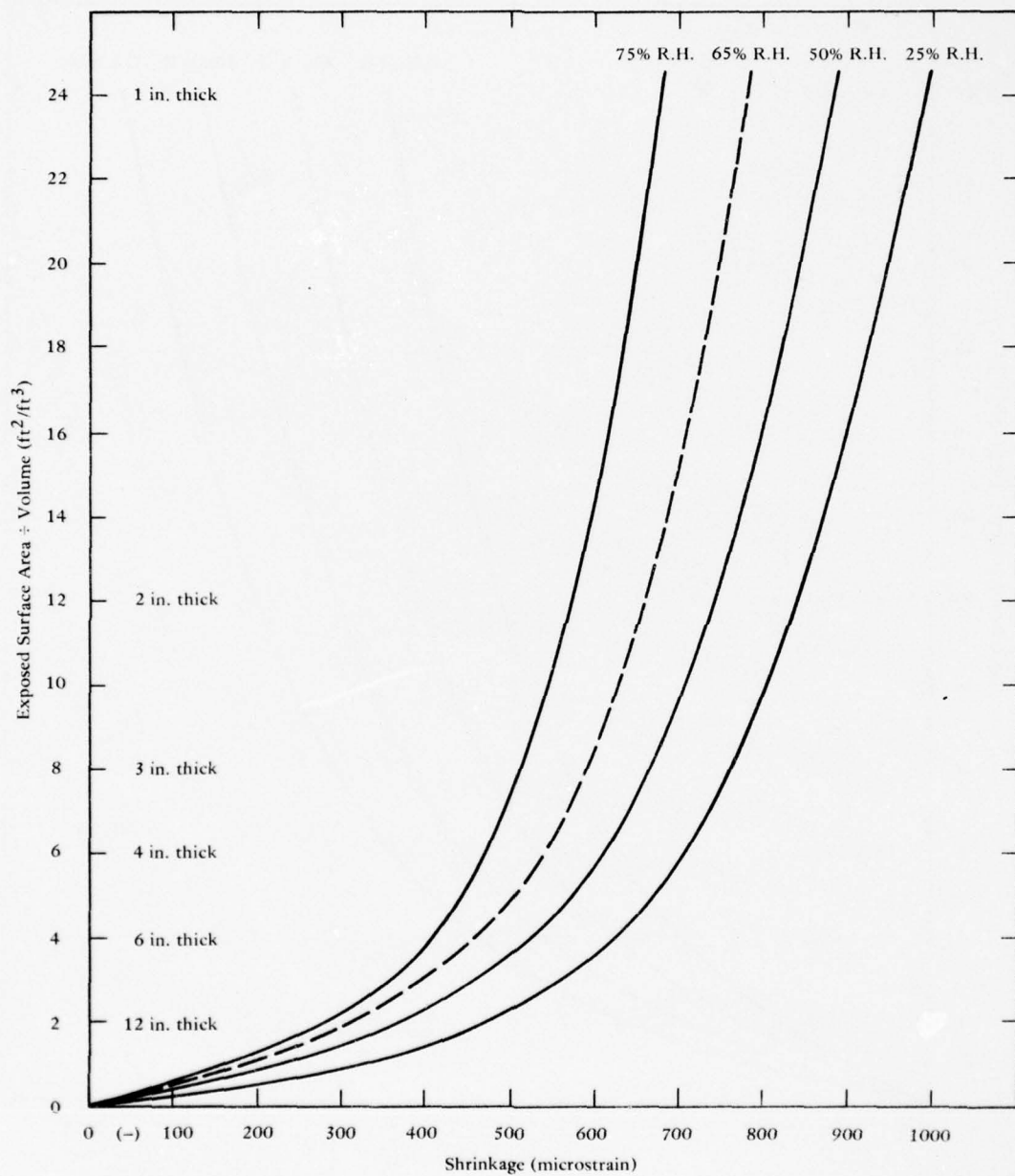
(a) Made with normal weight aggregate.

Figure 30. Shrinkage versus humidity for 7.5 SC concretes.



(b) Made with lightweight aggregates.

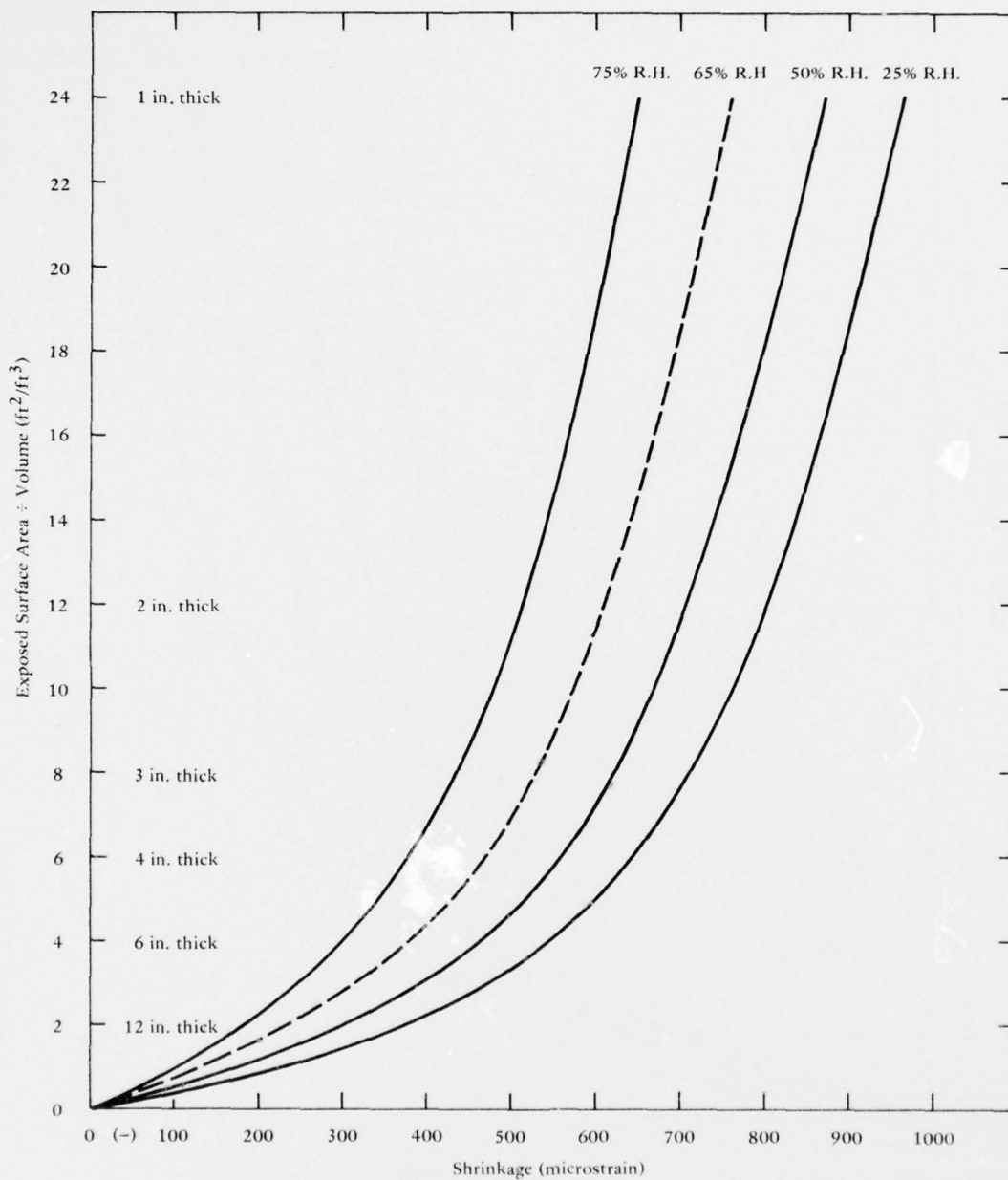
Figure 30. Continued



(a) Made with normal weight aggregates.

Figure 31. Shrinkage versus S/V for 7.5 SC concretes.





(b) Made with lightweight aggregates.

Figure 31. Continued

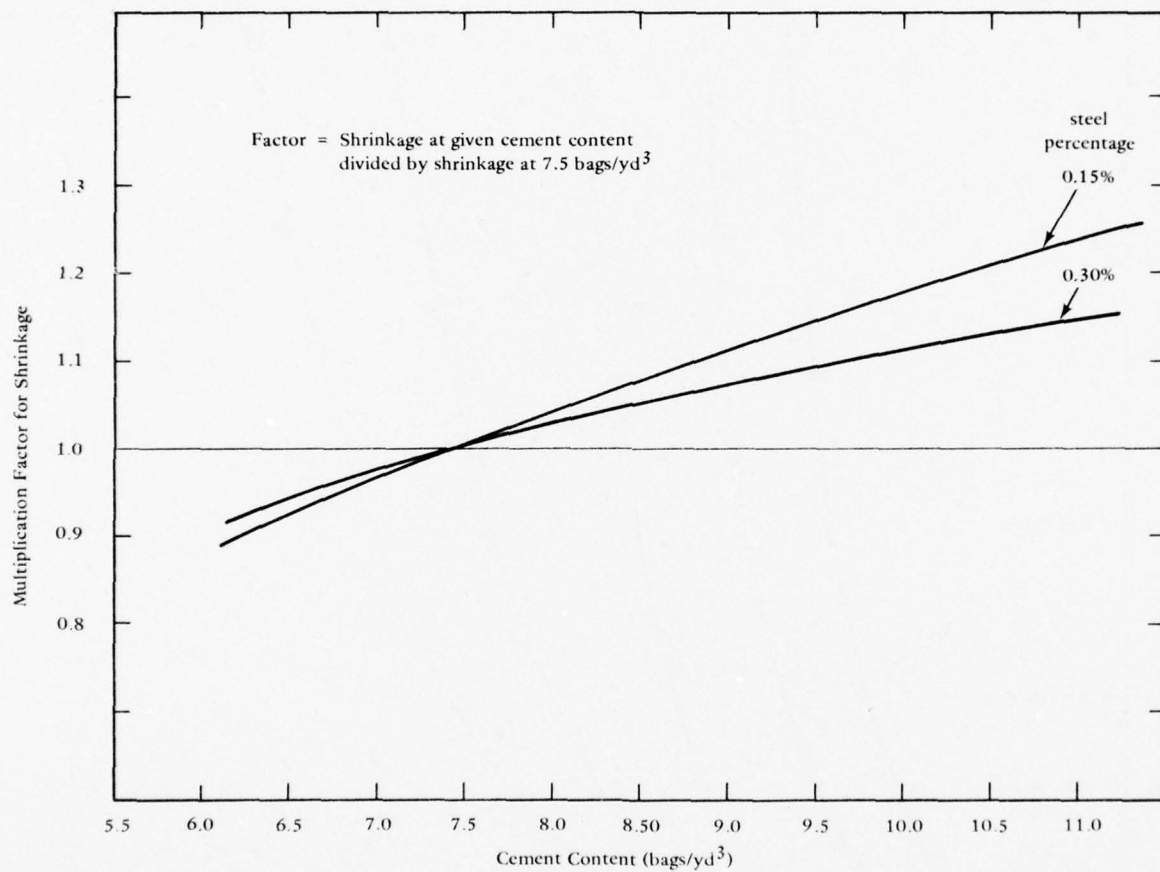
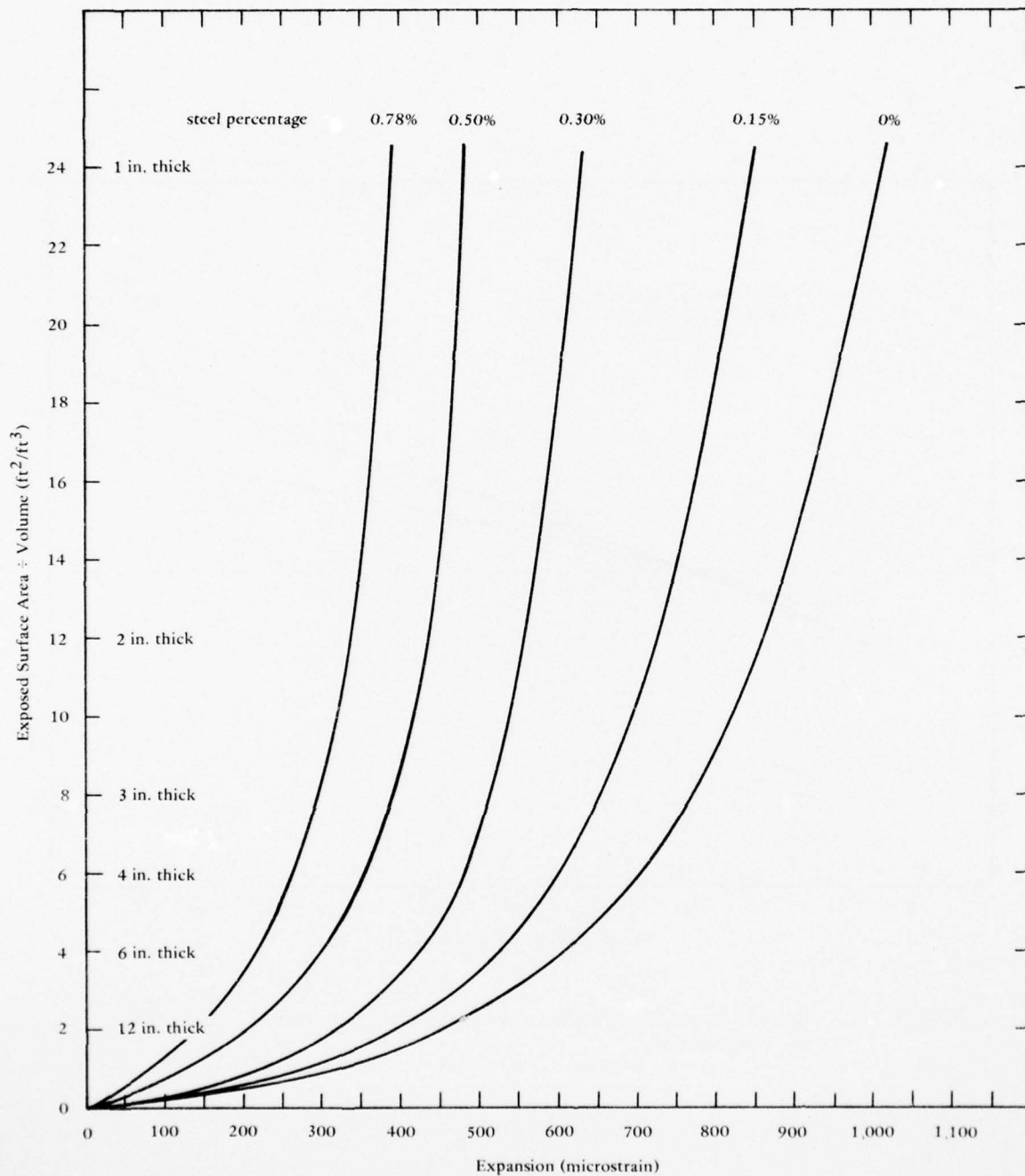
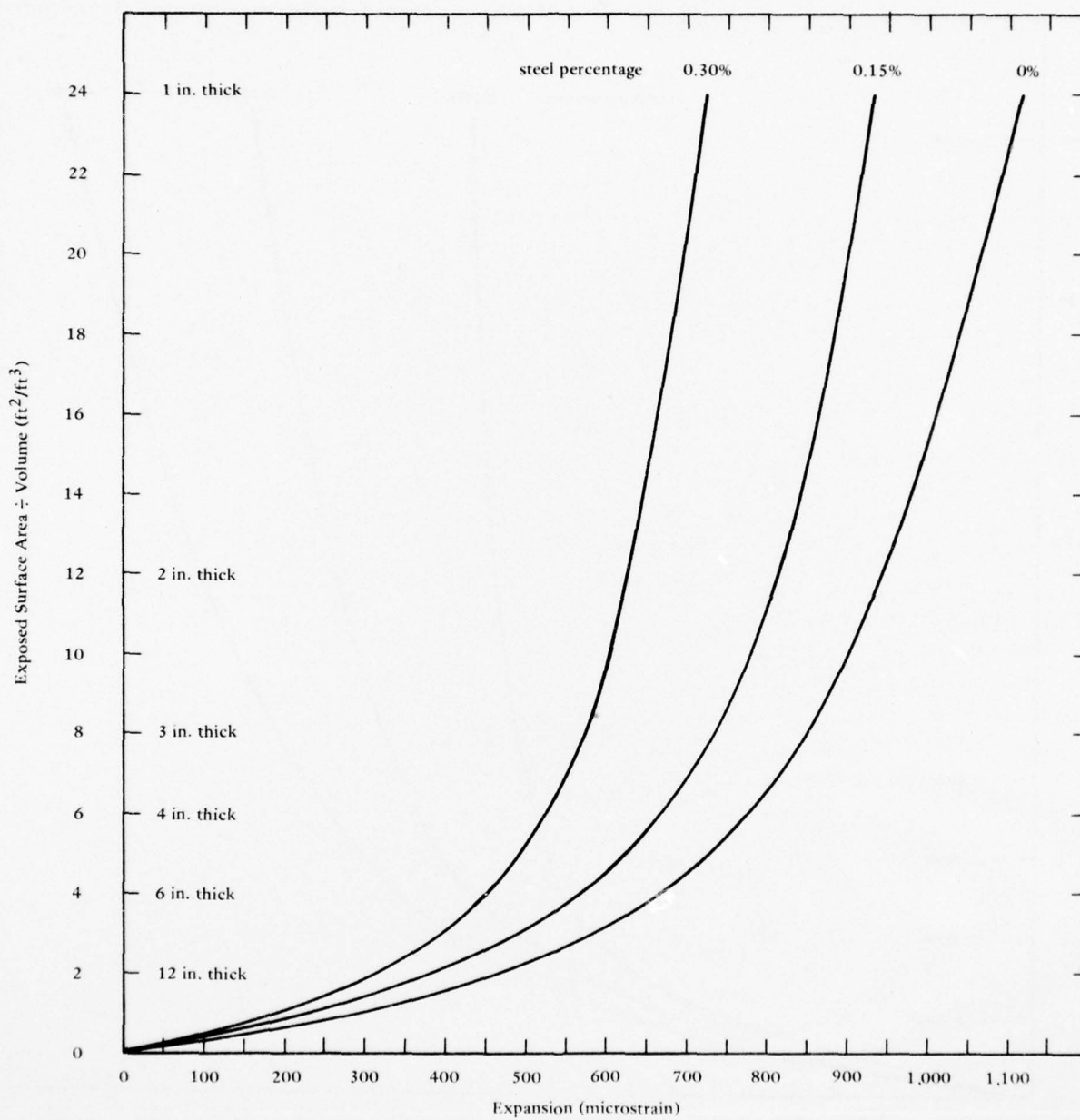


Figure 32. Multiplication factors for effects of cement content on shrinkage.



(a) Made with normal weight aggregates.

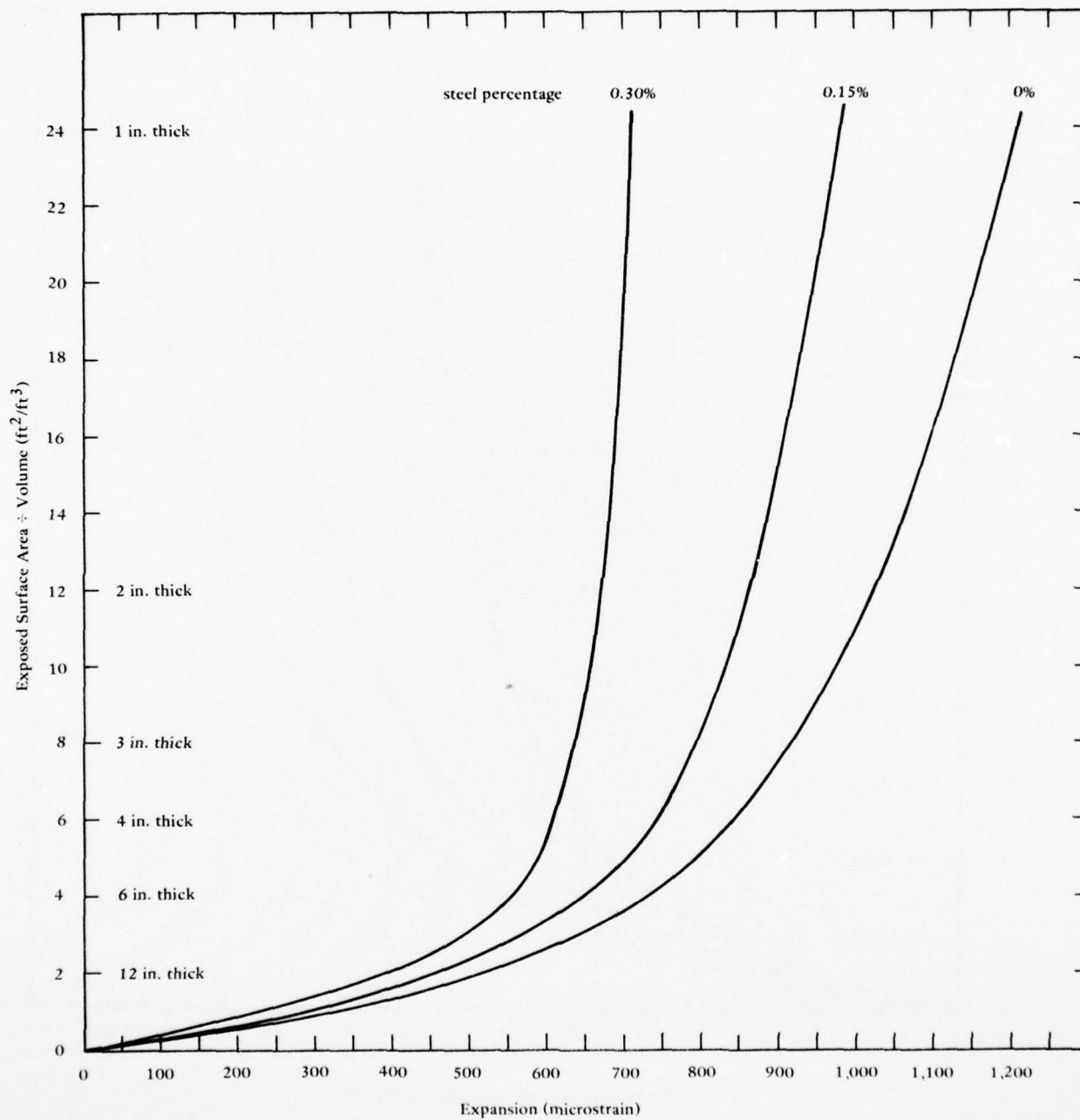
Figure 33. Expansion after 14 days of curing versus S/V for 7.5 SC concretes.



(b) Made with sand-lightweight aggregates.

Figure 33. Continued





(c) Made with all-lightweight aggregates.

Figure 33. Continued

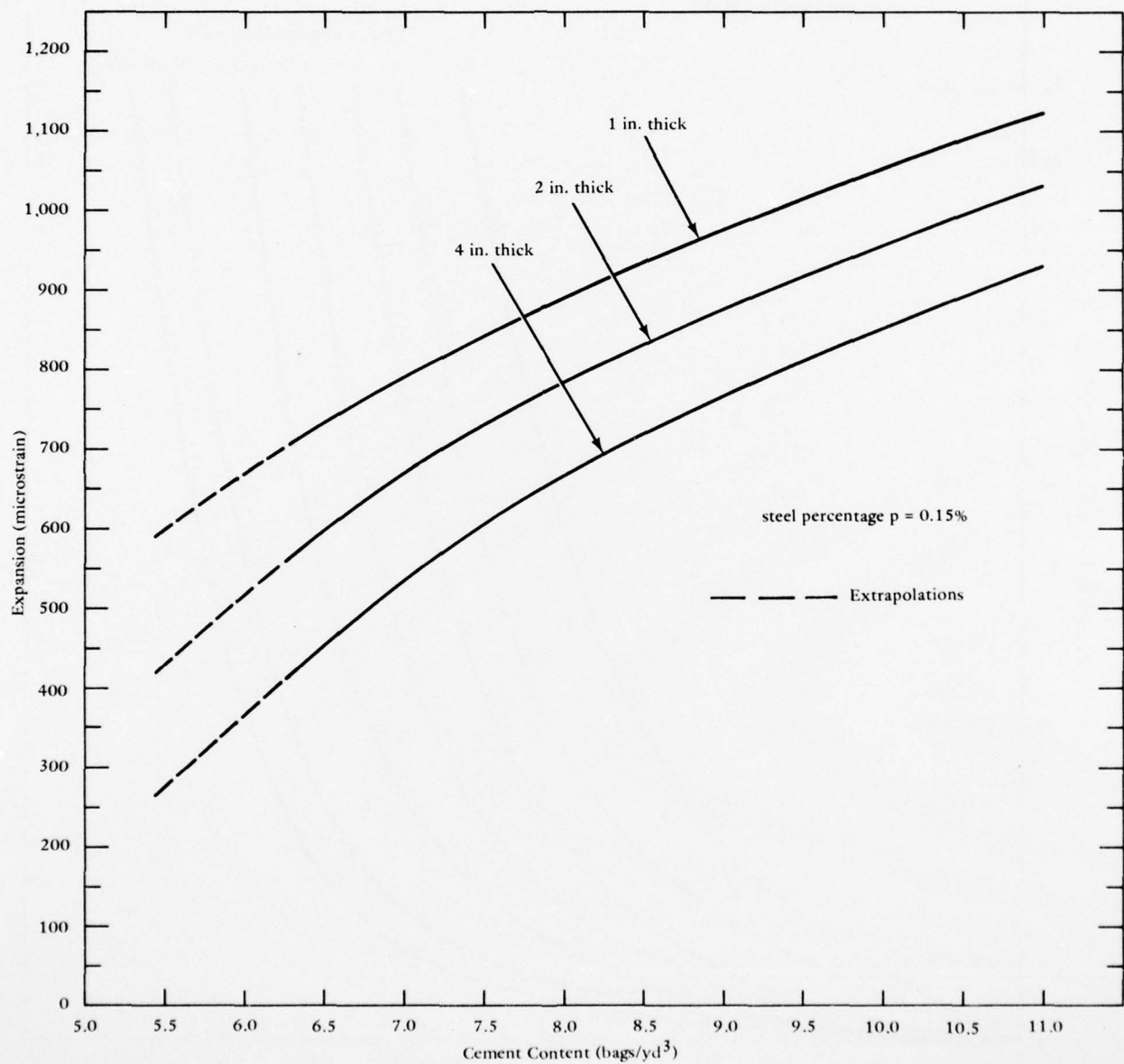


Figure 34. Expansion after 14 days of curing versus cement content for normal weight SC concretes.

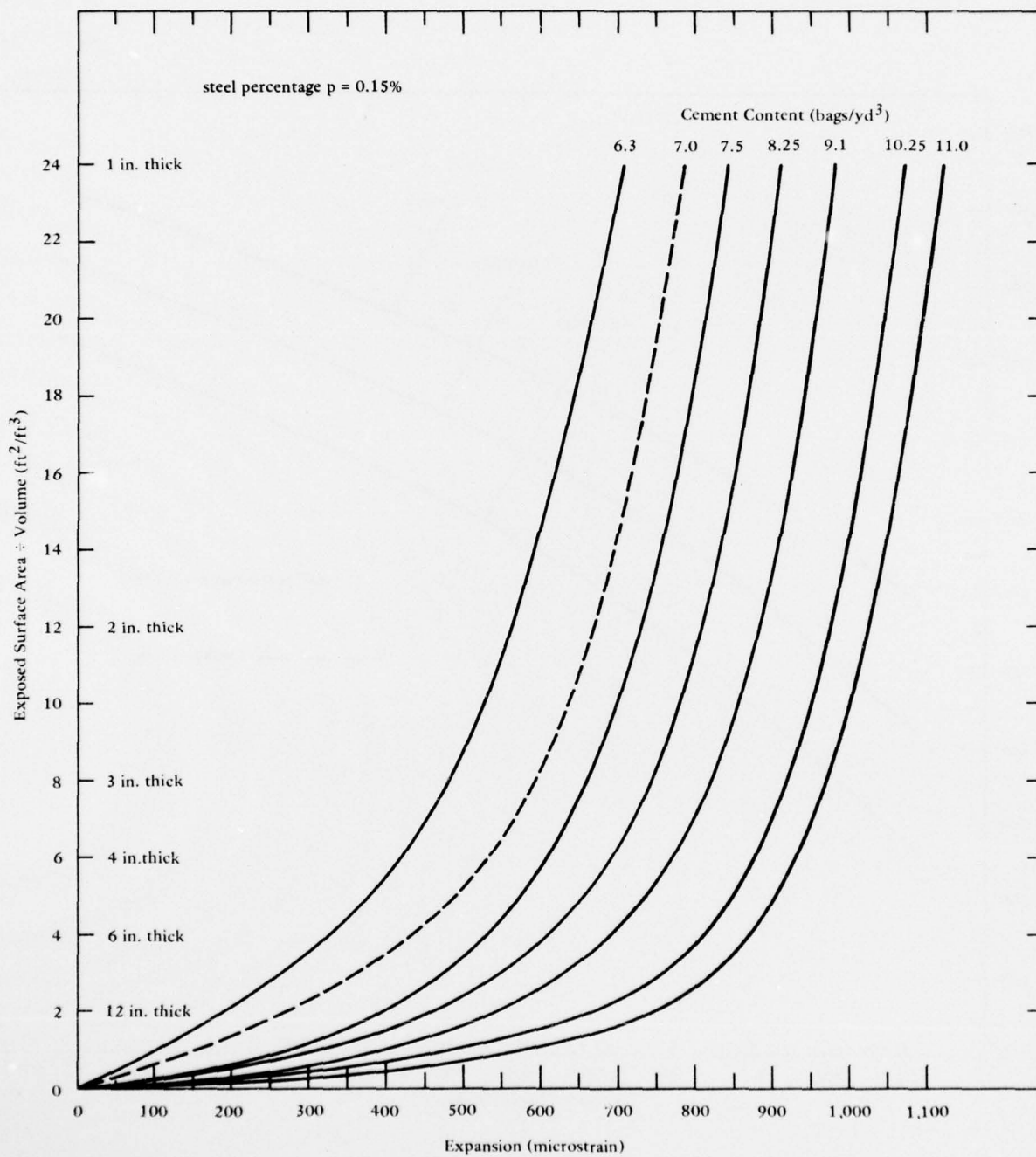


Figure 35. Expansion after 14 days of curing versus S/V for normal weight SC concretes made with different cement contents.

## DISTRIBUTION LIST

AFB (AFIT/LD), Wright-Patterson OH; AFCEC/XR, Tyndall FL; CESCH, Wright-Patterson; HQ Tactical Air Cmd (R. E. Fisher), Langley AFB VA; MAC/DET (Col. P. Thompson) Scott, IL; SAMSO/MNMF, Norton AFB CA; Stinfo Library, Offutt NE

ARMY AMSEL-GG-TD, Fort Monmouth NJ; BMDSC-RE (H. McClellan) Huntsville AL; DAEN-CWE-M (LT C D Binning), Washington DC; DAEN-FEU, Washington DC; DAEN-FEU-E (J. Ronan), Washington DC; DAEN-MCE-D Washington DC; HQ-DAEN-FEB-P (Mr. Price); Tech. Ref. Div., Fort Huachuca, AZ

ARMY - CERL Library, Champaign

ARMY BALLISTIC RSCH LABS, VA-LB, Aberdeen Proving Ground MD

ARMY COASTAL ENGR RSCH CEN, Fort Belvoir VA; R. Jachowski, Fort Belvoir VA

ARMY CORPS OF ENGINEERS MRI, Div., Omaha NE; Seattle Dist. Library, Seattle WA

ARMY CRREL Constr. Engr Res Branch, (mot)

ARMY DEV READINESS COM AMCPM-CS (J. Carr), Alexandria VA

ARMY ENG DIV ED-CS (S. Bolin) Huntsville, AL; HNDED-CS, Huntsville AL

ARMY ENG WATERWAYS EXP STAG G.C. Hoff, Vicksburg, MS; Library, Vicksburg MS

ARMY ENGR DIST. Library, Portland OR

ARMY ENVIRON. HYGIENE AGCY Water Qual Div (Doner), Aberdeen Prov Ground, MD

ARMY MATERIALS & MECHANICS RESEARCH CENTER Dr. Lenoe, Watertown MA

ARMY MISSILE R&DCMD Redstone Arsenal AL Sci. Info. Cen (Documents)

ARMY MOBIL EQUIP R&DCOM Mr. Cevasco, Fort Belvoir MD

ARMY TRANSPORTATION SCHOOL MAJ T Sweeney, Code ATSP-CPO-MS Fort Eustis VA

ARMY-PLASTEC Picatinny Arsenal (A M Anzalone, SMUPA-FR-M-D) Dover NJ

ASST SECRETARY OF THE NAVY Spec. Assist Energy (P. Waterman), Washington DC

BUREAU OF COMMERCIAL FISHERIES Woods Hole MA (Biological Lab. Lib.)

BUREAU OF RECLAMATION Code 1512 (C. Selander) Denver CO

MCB ENS S.D. Keisling, Quantico VA

CINCLANT Civil Engr. Supp. Plans. Ofc Norfolk, VA

CINCPAC Fac Engrng Div (J44) Makalapa, HI

CNAVRES Code 13 (Dir. Facilities) New Orleans, LA

CNM Code MAT-08T3, Washington, DC; NMAT 08T246 (Dieterle) Wash, DC

CNO Code NOP-964, Washington DC; OP987J (J. Boosman), Pentagon

COMCBPAC Operations Off, Makalapa HI

COMFAIRWESTPAC Security Offr, Misawa Japan

COMFLEACT, OKINAWA PWO, Kadena, Okinawa

COMNAVMARIANAS Code N4, Guam; FCE, Guam

COMOCEANSYSPAC SCE, Pearl Harbor HI

COMSUBDEVGRUONE Operations Offr, San Diego, CA

DEFENSE CIVIL PREPAREDNESS AGENCY J.O. Buchanan, Washington DC

DEFENSE DOCUMENTATION CTR Alexandria, VA

DEFENSE INTELLIGENCE AGENCY Dir., Washington DC

DNA STTL, Washington DC

DOD Explosives Safety Board (Library), Washington DC

DTNSRDC Code 1706, Bethesda MD; Code 172 (M. Krenzke), Bethesda MD

DTNSRDC Code 284 (A. Rufolo), Annapolis MD

DTNSRDC Code 4111 (R. Gierich), Bethesda MD

DTNSRDC Code 4121 (R. Rivers), Annapolis, MD

DTNSRDC Code 42, Bethesda MD

ENERGY R&D ADMIN. Dr. Cohen; INEL Tech. Lib. (Reports Section), Idaho Falls ID

FLTCOMBATTRACENLANT PWO, Virginia Bch VA

FMFLANT CEC Offr, Norfolk VA

GSA Fed. Sup. Serv. (FMBP), Washington DC

HEDSUPPACT PWO, Taipei, Taiwan

KWAJALEIN MISRAN BMDSC-RKL-C

MARINE CORPS BASE Camp Pendleton CA 92055; Code 43-260, Camp Lejeune NC; M & R Division, Camp Lejeune NC; PWO, Camp S. D. Butler, Kawasaki Japan



MARINE CORPS DIST 9, Code 043, Overland Park KS  
MARINE CORPS HQS Code LFF-2, Washington DC  
MCAS Facil. Engr. Div. Cherry Point NC; CO, Kaneohe Bay HI; Code PWE, Kaneohe Bay HI; Code S4, Quantico  
VA; J. Taylor, Iwakuni Japan; PWD, Dir. Maint. Control Div., Iwakuni Japan; PWO Kaneohe Bay HI; PWO,  
Yuma AZ  
MCDEC NSAP REP, Quantico VA; P&S Div Quantico VA  
MCLSB B520, Barstow CA  
MCRDPWO, San Diego Ca  
NAD Code 011B-1, Hawthorne NV; Dir. PW Eng. Div. McAlester, OK; Engr. Dir. Hawthorne, NV; PWD Nat./Resr.  
Mgr Forester, McAlester OK  
NAF PWO Sigonella Sicily; PWO, Atsugi Japan  
NAS Asst C/S CE Corpus Christi, TX; CO, Guantanamo Bay Cuba; Code 114, Alameda CA; Code 183 (Fac. Plan BR  
MGR); Code 18700, Brunswick ME; Code 6234 (G. Trask), Point Mugu CA; Code 70, Atlanta, Marietta GA; Dir.  
Maint. Control Div., Key West FL; Dir. Util. Div., Bermuda; ENS Buchholz, Pensacola, FL; Lakehurst, NJ;  
Lead. Chief, Petty Offr. PW/Self Help Div, Beeville TX; OIC, CBU 417, Oak Harbor WA; PW (J. Maguire), Corpus  
Christi TX; PWD (M.B. Trewitt), Dallas TX; PWD Maint. Cont. Dir., Fallon NV; PWD Maint. Div., New Orleans,  
Belle Chasse LA; PWD, Maintenance Control Dir., Bermuda; PWD, Willow Grove PA; PWO (M. Elliott), Los  
Alamos CA; PWO Belle Chasse, LA; PWO Chase Field Beeville, TX; PWO Key West FL; PWO Whiting Fld,  
Milton FL; PWO, Dallas TX; PWO, Glenview IL; PWO, Kingsville TX; PWO, Millington TN; PWO, Miramar, San  
Diego CA; PWO, Moffett Field CA; ROICC Key West FL; SCE Lant Fleet Norfolk, VA; SCE Norfolk, VA;  
SCE, Barbers Point HI  
NATL BUREAU OF STANDARDS B-348 BR (Dr. Campbell), Washington DC  
NATL RESEARCH COUNCIL Naval Studies Board, Washington DC  
NATNAVMEDECEN PWO Bethesda, MD  
NATPARACHUTETESTRAN PW Engr, El Centro CA  
NAVACT PWO, London UK  
NAVACTDET PWO, Holy Lock UK  
NAVAEROSPREGMEDECEN SCE, Pensacola FL  
NAVAL FACILITY PWO, Barbados; PWO, Brawdy Wales UK; PWO, Cape Hatteras, Buxton NC; PWO, Centerville  
Bch, Ferndale CA; PWO, Guam  
NAVAVIONICFAC PWD Deputy Dir. D/701, Indianapolis, IN  
NAVCOASTSYS LAB CO, Panama City FL; Code 423 (D. Good), Panama City FL; Code 715 (J. Mittleman) Panama  
City, FL; Code 715 (J. Quirk) Panama City, FL; Code 772 (C B Koesy) Panama City FL; Library Panama City, FL  
NAVCOMMAREAMSTRSTA Code W-602, Honolulu, Wahiawa HI; PWO, Norfolk VA; PWO, Wahiawa HI; SCE  
Unit 1 Naples Italy  
NAVCOMMSTA Code 401 Nea Makri, Greece; PWO, Adak AK; PWO, Fort Amador Canal Zone  
NAVCOMMUNIT Cutler/E. Machias ME (PW Gen. For.)  
NAVCONSTRACEN CO (CDR C.L. Neugent), Port Hueneme, CA  
NAVEDTRAPRODEVEN Tech. Library  
NAVENVIRHLTHCEN CO, Cincinnati, OH  
NAVEODFAC Code 605, Indian Head MD  
NAVFAC PWO, Lewes DE  
NAVFACENGCOM Code 043 Alexandria, VA; Code 044 Alexandria, VA; Code 0451 Alexandria, VA; Code 0453 (D.  
Potter) Alexandria, VA; Code 0454B Alexandria, VA; Code 046; Code 0461D (V M Spaulding); Code 04B3  
Alexandria, VA; Code 04B5 Alexandria, VA; Code 101 Alexandria, VA; Code 10133 (J. Leimanis) Alexandria, VA;  
Code 1023 (M. Carr) Alexandria, VA; Code 1023 (T. Stevens) Alexandria, VA; Code 104 Alexandria, VA; Code  
2014 (Mr. Taam), Pearl Harbor HI; P W Brewer; PC-22 (E. Spencer) Alexandria, VA; PL-2 Ponce P.R. Alexandria,  
VA  
NAVFACENGCOM - CHES DIV. Code 101 Wash, DC; Code 402 (R. Morony) Wash, DC; Code 403 (H. DeVoe)  
Wash, DC; Code 405 Wash, DC; Code FPO-1 (C. Bodey) Wash, DC; Code FPO-1 (Ottson) Wash, DC; Code  
FPO-ISP (Dr. Lewis) Wash, DC; Code FPO-ISP13 (T F Sullivan) Wash, DC; Code FPO-IP12 (Mr. Scola),  
Washington DC; Contracts, ROICC, Annapolis MD  
NAVFACENGCOM - LANT DIV. Code 10A, Norfolk VA; Eur. BR Deputy Dir, Naples Italy; RDT&ELO 09P2,  
Norfolk VA  
NAVFACENGCOM - NORTH DIV. AROICC, Brooklyn NY; CO; Code 09P (LCDR A.J. Stewart); Code 1028,  
RDT&ELO, Philadelphia PA; Code 111 (Castronovo); Code 114 (A. Rhoads); Design Div. (R. Masino), Philadelphia  
PA; ROICC, Contracts, Crane IN  
NAVFACENGCOM - PAC DIV. Code 402, RDT&E, Pearl Harbor HI; Commander, Pearl Harbor, HI

NAVFACENGCOM - SOUTH DIV. Code 90, RDT&ELO, Charleston SC; Dir., New Orleans LA; ROICC (LCDR R. Moeller), Contracts, Corpus Christi TX  
 NAVFACENGCOM - WEST DIV. 102; 112; 408, San Bruno CA; AROICC, Contracts, Twentynine Palms CA; Code 04B; 09P/20; RDT&ELO Code 2011 San Bruno, CA  
 NAVFACENGCOM CONTRACT AROICC, Point Mugu CA; AROICC, Quantico, VA; Code 05, TRIDENT, Bremerton WA; Eng Div dir, Southwest Pac, Manila, PI; OICC, Southwest Pac, Manila, PI; OICC/ROICC, Balboa Canal Zone; ROICC (Ervin) Puget Sound Naval Shipyard, Bremerton, WA; ROICC (LCDR J.G. Leech), Subic Bay, R.P.; ROICC LANT DIV., Norfolk VA; ROICC Off Point Mugu, CA; ROICC, Clark AFB, PI; ROICC, Diego Garcia Island; ROICC, Keflavik, Iceland; ROICC, Pacific, San Bruno CA  
 NAVHOSP LT R. Elsbernd, Puerto Rico  
 NAVMAG SCE, Guam  
 NAVMIRO OIC, Philadelphia PA  
 NAVNUPWRU MUSE DET OIC, Port Hueneme CA  
 NAVOCEANO Code 1600 Bay St. Louis, MS; Code 3432 (J. DePalma), Bay St. Louis MS  
 NAVOCEANSYSCEN Code 6565 (Tech. Lib.), San Diego CA; Code 6700, San Diego, CA; Code 7511 (PWO) San Diego, CA; SCE (Code 6600), San Diego CA  
 NAVORDSTA PWO, Louisville KY  
 NAVPETOFF Code 30, Alexandria VA  
 NAVPGSCOL LCDR K.C. Kelley Monterey CA  
 NAVPHIBASE CO, ACB 2 Norfolk, VA; Code S3T, Norfolk VA; OIC, UCT ONE Norfolk, Va; UCT 1 (MacDougal) Norfolk, VA  
 NAVRADREC FAC PWO, Kami Seya Japan  
 NAVREGMEDCEN Code 3041, Memphis, Millington TN; PWO Newport RI; PWO Portsmouth, VA; SCE (D. Kaye); SCE (LCDR B. E. Thurston), San Diego CA; SCE, Guam  
 NAVSCOLCECOFF C35 Port Hueneme, CA; C44A (R. Chittenden), Port Hueneme CA; CO, Code C44A Port Hueneme, CA  
 NAVSEASYS COM Code 0325, Program Mgr, Washington, DC; Code SEA OOC Washington, DC  
 NAVSEC Code 6034 (Library), Washington DC  
 NAVSECGRUACT Facil. Off., Galeta Is. Canal Zone; PWO, Edzell Scotland; PWO, Puerto Rico; PWO, Torri Sta, Okinawa  
 NAVSHIPREPFAC Library, Guam; SCE Subic Bay  
 NAVSHIPYD CO Marine Barracks, Norfolk, Portsmouth VA; Code 202.4, Long Beach CA; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 400, Puget Sound; Code 404 (LT J. Riccio), Norfolk, Portsmouth VA; Code 410, Mare Is., Vallejo CA; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; Code 440.4, Charleston SC; Code 450, Charleston SC; L.D. Vivian; Library, Portsmouth NH; PWD (Code 400), Philadelphia PA; PWD (LT N.B. Hall), Long Beach CA; PWO, Mare Is.; PWO, Puget Sound; SCE, Pearl Harbor HI  
 NAVSTA CO Naval Station, Mayport FL; CO Roosevelt Roads P.R. Puerto Rico; Engr. Dir., Rota Spain; Maint. Cont. Div., Guantanamo Bay Cuba; Maint. Div. Dir/Code 531, Rodman Canal Zone; PWD (LTJG P.M. Motodlenich), Puerto Rico; PWD/Engr. Div. Puerto Rico; PWO Midway Island; PWO, Guantanamo Bay Cuba; PWO, Keflavik Iceland; PWO, Mayport FL; PWO, Puerto Rico; ROICC Rota Spain; ROICC, Rota Spain; SCE, Guam; SCE, San Diego CA; SCE, Subic Bay, R.P.; Utilities Engr Off. (LTJG A.S. Ritchie), Rota Spain  
 NAVSUBASE LTJG D.W. Peck, Groton, CT  
 NAVSUPPACT CO, Brooklyn NY; CO, Seattle WA; Code 4, 12 Marine Corps Dist, Treasure Is., San Francisco CA; Engr. Div. (F. Mollica), Naples Italy; LTJG McGarragh, Vallejo CA; Plan/Engr Div., Naples Italy  
 NAVSURFWPNCEN PWO, White Oak, Silver Spring, MD  
 NAVTECHTRACEN SCE, Pensacola FL  
 NAVWPNCEN Code 2636 (W. Bonner), China Lake CA; PWO (Code 26), China Lake CA; ROICC (Code 702), China Lake CA  
 NAVWPNSTA ENSG.A. Lowry, Fallbrook CA; Maint. Control Dir., Yorktown VA; PW Office (Code 09C1) Yorktown, VA; PWO, Seal Beach CA  
 NAVWPNSUPPCEN Code 09 (Boennighausen) Crane IN  
 NAVXDIVING LT A.M. Parisi, Panama City FL  
 WPNSTA EARLE Code 092, Colts Neck NJ  
 NCBC CEL (CAPT N. W. Petersen), Port Hueneme, CA; CEL AOIC Port Hueneme CA; Code 10 Davisville, RI; Code 400, Gulfport MS; PW Engrg, Gulfport MS; PWO (Code 80) Port Hueneme, CA  
 NCBU 411 OIC, Norfolk VA

NCR 20, Commander  
 NMCB 133 (ENST.W. Nielsen); 5, Operations Dept.; 74, CO; Forty, CO; THREE, Operations Off.  
 NRL Code 8400 (J. Walsh), Washington DC; Code 8441 (R.A. Skop), Washington DC  
 NROTCU Univ Colorado (LT DR Burns), Boulder CO  
 NSC Code 54.1 (Wynne), Norfolk VA  
 NSD SCE, Subic Bay, R.P.  
 NTC Code 54 (ENS P. G. Jackel), Orlando FL; Commander Orlando, FL; OICC, CBU-401, Great Lakes IL; SCE  
 Great Lakes, IL  
 NUSC Code 131 New London, CT; Code EA123 (R.S. Munn), New London CT; Code TA131 (G. De la Cruz), New  
 London CT  
 OCEANSYSLANT LT A.R. Giancola, Norfolk VA  
 NORDA Code 440 (Ocean Rsch, off) Bay St. Louis, Ms  
 ONR BROFF, CO Boston MA; Code 700F Arlington VA; Dr. A. Laufer, Pasadena CA  
 PACMISRANFAC CO, Kekaha HI  
 PMTC Code 4253-3, Point Mugu, CA; Pat. Counsel, Point Mugu CA  
 PW ENS J.E. Surash, Pearl Harbor HI; ACE Office (LTJG St. Germain) Norfolk VA; CO, Great Lakes IL; Code  
 116 (LTJG. A. Eckhart) Great Lakes, IL; Code 120, Oakland CA; Code 120C (Library) San Diego, CA; Code 128,  
 Guam; Code 200, Great Lakes IL; Code 200, Oakland CA; Code 220 Oakland, CA; Code 220.1, Norfolk VA; Code  
 30C (Boettcher) San Diego, CA; Code 40 (C. Kolton) Pensacola, FL; Code 505A (H. Wheeler); Code 680, San  
 Diego CA; Library, Subic Bay, R.P.; OIC CBU-405, San Diego CA; XO Oakland, CA  
 SPCC Code 122B, Mechanicsburg, PA; PWO (Code 120) Mechanicsburg PA  
 UCT TWO OIC, Port Hueneme CA  
 U.S. MERCHANT MARINE ACADEMY Kings Point, NY (Reprint Custodian)  
 US DEPT OF AGRIC Forest Products Lab, Madison WI  
 US NAVAL FORCES Korea (ENJ-P&O)  
 USAF SCHOOL OF AEROSPACE MEDICINE Hyperbaric Medicine Div, Brooks AFB, TX  
 USCG (G-ECV/61) (Burkhart) Washington, DC; G-EOE-4/61 (T. Dowd), Washington DC; MMT-4, Washington DC  
 USCG ACADEMY LT N. Stramandi, New London CT  
 USCG R&D CENTER Tech. Dir. Groton, CT  
 USNA Ch. Mech. Engr. Dept Annapolis MD; Ocean Sys. Eng Dept (Dr. Monney) Annapolis, MD; PWD Engr. Div.  
 (C. Bradford) Annapolis MD; PWO Annapolis MD  
 AMERICAN CONCRETE INSTITUTE Detroit MI (Library)  
 CALIF. DEPT OF NAVIGATION & OCEAN DEV. Sacramento, CA (G. Armstrong)  
 CALIF. MARITIME ACADEMY Vallejo, CA (Library)  
 CALIFORNIA STATE UNIVERSITY LONG BEACH, CA (CHELAPATI)  
 CORNELL UNIVERSITY Ithaca NY (Serials Dept, Engr Lib.)  
 DAMES & MOORE LIBRARY LOS ANGELES, CA  
 DUKE UNIV MEDICAL CENTER B. Muga, Durham NC  
 FLORIDA ATLANTIC UNIVERSITY BOCA RATON, FL (MC ALLISTER); Boca Raton FL (Ocean Engr Dept., C.  
 Lin)  
 FLORIDA ATLANTIC UNIVERSITY Boca Raton FL (W. Tessin)  
 FLORIDA TECHNOLOGICAL UNIVERSITY ORLANDO, FL (HARTMAN)  
 GEORGIA INSTITUTE OF TECHNOLOGY Atlanta GA (School of Civil Engr., Kahn)  
 INSTITUTE OF MARINE SCIENCES Morehead City NC (Director)  
 IOWA STATE UNIVERSITY Ames IA (CE Dept, Handy)  
 VIRGINIA INST. OF MARINE SCI. Gloucester Point VA (Library)  
 LEHIGH UNIVERSITY BETHLEHEM, PA (MARINE GEOTECHNICAL LAB., RICHARDS); Bethlehem PA  
 (Fritz Engr. Lab No. 13, Beedle); Bethlehem PA (Linderman Lib. No. 30, Flecksteiner)  
 LIBRARY OF CONGRESS WASHINGTON, DC (SCIENCES & TECH DIV)  
 MAINE MARITIME ACADEMY CASTINE, ME (LIBRARY)  
 MICHIGAN TECHNOLOGICAL UNIVERSITY Houghton, MI (Haas)  
 MIT Cambridge MA; Cambridge MA (Rm 10-500, Tech. Reports, Engr. Lib.); Cambridge MA (Whitman)  
 NY CITY COMMUNITY COLLEGE BROOKLYN, NY (LIBRARY)  
 UNIV. NOTRE DAME Katona, Notre Dame, IN  
 OREGON STATE UNIVERSITY (CE Dept Grace) Corvallis, OR; CORVALLIS, OR (CE DEPT, BELL);  
 CORVALLIS, OR (CE DEPT, HICKS); Corvallis OR (School of Oceanography)  
 PENNSYLVANIA STATE UNIVERSITY STATE COLLEGE, PA (SNYDER); UNIVERSITY PARK, PA  
 (GOTOLSKI)



PURDUE UNIVERSITY Lafayette IN (Leonards); Lafayette, IN (Altschaeffl); Lafayette, IN (CE Engr. Lib)  
 SAN DIEGO STATE UNIV. Dr. Krishnamoorthy, San Diego CA  
 SCRIPPS INSTITUTE OF OCEANOGRAPHY LA JOLLA, CA (ADAMS); San Diego, CA (Marina Phy. Lab. Spiess)  
 SOUTHWEST RSCH INST J. Maison, San Antonio TX; R. DeHart, San Antonio TX  
 STANFORD UNIVERSITY Stanford CA (Gene)  
 STATE UNIV. OF NEW YORK Buffalo, NY  
 TEXAS A&M UNIVERSITY COLLEGE STATION, TX (CE DEPT); College TX (CE Dept, Herbich)  
 UNIVERSITY OF CALIFORNIA BERKELEY, CA (CE DEPT, GERWICK); BERKELEY, CA (CE DEPT,  
 MITCHELL); BERKELEY, CA (OFF. BUS. AND FINANCE, SAUNDERS); Berkeley CA (B. Bresler);  
 Berkeley CA (Dept of Naval Arch.); Berkeley CA (E. Pearson); Berkeley CA (M. Polivka) Dept of CE; Berkeley  
 CA (R. Williamson); DAVIS, CA (CE DEPT, TAYLOR); LIVERMORE, CA (LAWRENCE LIVERMORE LAB,  
 TOKARZ); Los Angeles S. Aroni; M. Duncan, Berkeley CA  
 UNIVERSITY OF DELAWARE Newark, DE (Dept of Civil Engineering, Chesson)  
 UNIVERSITY OF HAWAII HONOLULU, HI (SCIENCE AND TECH. DIV.); Honolulu HI (Dr. Szilard)  
 UNIVERSITY OF ILLINOIS Metz Ref Rm, Urbana IL; URBANA, IL (DAVISSON); URBANA, IL (LIBRARY);  
 URBANA, IL (NEWARK); Urbana IL (CE Dept, W. Gamble); Urbana IL (Kesler)  
 UNIVERSITY OF MASSACHUSETTS (Heronemus), Amherst MA CE Dept  
 UNIVERSITY OF MICHIGAN Ann Arbor MI (Richart)  
 UNIVERSITY OF NEBRASKA-LINCOLN Lincoln, NE (Ross Ice Shelf Proj.)  
 UNIVERSITY OF NEW MEXICO Albuquerque NM (Soil Mech. & Pav. Div., J. Nielsen)  
 UNIVERSITY OF PENNSYLVANIA PHILADELPHIA, PA (SCHOOL OF ENGR & APPLIED SCIENCE, ROLL)  
 UNIVERSITY OF TEXAS Inst. Marine Sci (Library), Port Arkansas TX  
 UNIVERSITY OF TEXAS AT AUSTIN AUSTIN, TX (THOMPSON); Austin, TX (Breen)  
 UNIVERSITY OF WASHINGTON Dept of Civil Engr (Dr. Mattock), Seattle WA; SEATTLE, WA (MERCHANT);  
 SEATTLE, WA (OCEAN ENGR RSCH LAB, GRAY); Seattle WA (E. Linger); Seattle, WA Transportation,  
 Construction & Geom. Div  
 US DEPT OF COMMERCE NOAA, Marine & Earth Sciences Lib., Rockville MD  
 AEROSPACE CORP. Acquisition Group, Los Angeles CA  
 ALFRED A. YEE & ASSOC, Honolulu HI  
 APPLIED TECH COUNCIL R. Scholl, Palo Alto CA  
 ARVID GRANT OLYMPIA, WA  
 ATLANTIC RICHFIELD CO, DALLAS, TX (SMITH)  
 AUSTRALIA Dept. PW (A. Hicks), Melbourne  
 BECHTEL CORP. SAN FRANCISCO, CA (PHELPS)  
 BELGIUM HAECON, N.V., Gent  
 BETHLEHEM STEEL CO. BETHLEHEM, PA (STEELE)  
 C.W. BLAKESLEE & SONS D.W. Pfeifer New Haven CT  
 CANADA Can-Dive Services (English) North Vancouver; Mem Univ Newfoundland (Chari), St Johns; Surveyor,  
 Nenninger & Chenevert Inc., Montreal  
 CF BRAUN CO Du Bouchet, Murray Hill, NJ  
 CHEMED CORP Lake Zurich IL (Dearborn Chem. Div. Lib.)  
 CHEMICALLY PRESTRESSED CONCRETE CORP. W.P. Liljestrom, Los Angeles, CA  
 CHEVRON OIL FIELD RESEARCH CO. LA HABRA, CA (BROOKS)  
 COLUMBIA GULF TRANSMISSION CO. HOUSTON, TX (ENG. LIB.)  
 CONCRETE TECHNOLOGY CORP. TACOMA, WA (ANDERSON)  
 CONRAD ASSOC. Van Nuys CA (A. Luisoni)  
 DILLINGHAM PRECAST F. McHale, Honolulu HI  
 DRAVO CORP Pittsburgh PA (Giannino); Pittsburgh PA (Wright)  
 NORWAY DET NORSKE VERITAS (Library), Oslo  
 EVALUATION ASSOC. INC KING OF PRUSSIA, PA (FEDELE)  
 FORD, BACON & DAVIS, INC. New York (Library)  
 FRANCE Dr. Dutertre, Boulogne; L. Pliskin, Paris; P. Jensen, Boulogne; Roger LaCroix, Paris  
 GENERAL DYNAMICS Elec. Boat Div., Environ. Engr (H. Wallman), Groton CT  
 GEOTECHNICAL ENGINEERS INC. Winchester, MA (Paulding)  
 GLIDDEN CO. STRONGSVILLE, OH (RSCH LIB)  
 GLOBAL MARINE DEVELOPMENT NEWPORT BEACH, CA (HOLLETT)  
 GOULD INC. Shady Side MD (Ches. Inst. Div., W. Paul)  
 GRUMMAN AEROSPACE CORP. Bethpage NY (Tech. Info. Ctr)



HALEY & ALDRICH, INC. Cambridge MA (Aldrich, Jr.)  
 HONEYWELL, INC. Minneapolis MN (Residential Engr Lib.)  
 HUGHES AIRCRAFT Culver City CA (Tech. Doc. Ctr)  
 IDEAL CEMENT CO. E.G. Hedstrom, Denver, CO  
 ITALY M. Caironi, Milan; Sergio Tattoni Milano; Torino (F. Levi)  
 MAKAI OCEAN ENGRNG INC. Kailua, HI  
 JAMES CO. R. Girdley, Orlando FL  
 KAISER CEMENT & GYPSUM CORP. J.W. Post, Permanente, Ca  
 KENNETH TATOR ASSOC CORAOPOLIS, PA (LIBRARY)  
 LOCKHEED MISSILES & SPACE CO. INC. Mgr Naval Arch & Mar Eng Sunnyvale, CA; Sunnyvale CA  
 (Rynewicz); Sunnyvale, CA (Phillips)  
 LOCKHEED OCEAN LABORATORY SAN DIEGO, CA (PRICE)  
 LOUISVILLE CEMENT CO. H.C. Fischer, Speed, IN  
 MARATHON OIL CO Houston TX (C. Seay)  
 MARINE CONCRETE STRUCTURES INC. MEFAIRIE, LA (INGRAHAM)  
 MC CLELLAND ENGINEERS INC Houston TX (B. McClelland)  
 MCDONNELL AIRCRAFT CO. Dept 501 (R.H. Fayman), St Louis MO  
 MEDALL & ASSOC. INC. J.T. GAFFEY II SANTA ANA, CA  
 MEDUSA CEMENT CO. N.R. Yoder, Wampum, PA; P.W. Gutmann Cleveland OH  
 MEXICO R. Cardenas  
 MOBIL PIPE LINE CO. DALLAS, TX MGR OF ENGR (NOACK)  
 MUESER, RUTLEDGE, WENTWORTH AND JOHNSTON NEW YORK (RICHARDS)  
 NEW ZEALAND New Zealand Concrete Research Assoc. (Librarian), Porirua  
 NEWPORT NEWS SHIPBLDG & DRYDOCK CO. Newport News VA (Tech. Lib.)  
 NORWAY DET NORSKE VERITAS (Roren) Oslo; I. Foss, Oslo; J. Creed, Ski; Norwegian Tech Univ (Brandtzaeg),  
 Trondheim  
 OCEAN DATA SYSTEMS, INC. SAN DIEGO, CA (SNODGRASS)  
 OFFSHORE DEVELOPMENT ENG. INC. BERKELEY, CA  
 PACIFIC MARINE TECHNOLOGY LONG BEACH, CA (WAGNER)  
 PENN - DIXIE CEMENT CORP. O.J. Glantz, Nazareth, PA  
 PHOENIX CEMENT CORP. J.N. Stoss, Phoenix, AZ  
 PORTLAND CEMENT ASSOC. H.G. Russell, S Kokie, IL; SKOKIE, IL (CORELY); SKOKIE, IL (KLIEGER);  
 Skokie IL (Rsch & Dev Lab, Lib.)  
 PRESCON CORPTOWSON, MD (KELLER)  
 PUERTO RICO Puerto Rico (Rsch Lib.), Mayaguez P R  
 RAND CORP. Santa Monica CA (A. Laupa)  
 RAYMOND INTERNATIONAL INC. CHERRY HILL, NJ (SOILTECH DEPT)  
 RIVERSIDE CEMENT CO Riverside CA (W. Smith)  
 SANDIA LABORATORIES C.W. Gulick Jr. Albuquerque, NM; Library Div., Livermore CA  
 SCHUPACK ASSOC SO. NORWALK, CT (SCHUPACK)  
 SEAFOOD LABORATORY MOREHEAD CITY, NC (LIBRARY)  
 SEATECH CORP. MIAMI, FL (PERONI)  
 SHELL DEVELOPMENT CO. Houston TX (E. Doyle)  
 SHELL OIL CO. HOUSTON, TX (MARSHALL)  
 SOUTH AMERICAN. Nouel, Valencia, Venezuela  
 SOUTHWEST PORTLAND CEMENT CO. C.T. Test Los Angeles, CA  
 SWEDEN GeoTech Inst; VBB (Library), Stockholm  
 TECHNICAL COATINGS CO Oakmont PA (Library)  
 TEXAS IND., INC. J.V. Williams Arlington, TX  
 TIDEWATER CONSTR. CO Norfolk VA (Fowler)  
 TRW SYSTEMS CLEVELAND, OH (ENG. LIB.); REDONDO BEACH, CA (DAI)  
 U.S. STEEL CORP. J.L. Deets, Gary IN  
 UNITED KINGDOM Cement & Concrete Assoc (G. Somerville) Wexham Springs, Slou; Cement & Concrete Assoc.  
 (Library), Wexham Springs, Slough; Cement & Concrete Assoc. (Lit. Ex), Bucks; Cement & Concrete Assoc.  
 Bucks England (PE Nalstead); D. New, G. Maunsell & Partners, London; Library, Bristol; Shaw & Hatton (F.  
 Hansen), London; Taylor, Woodrow Constr (014P), Southall, Middlesex; Univ. of Bristol (R. Morgan), Bristol  
 WESTINGHOUSE ELECTRIC CORP. Annapolis MD (Oceanic Div Lib, Bryan); Library, Pittsburgh PA  
 WISS, JANNEY, ELSTNER, & ASSOC (J.a. Hanson) Northbrook, IL; Northbrook, IL (J. Hanson)

WM CLAPP LABS - BATTELLE DUXBURY, MA (LIBRARY); Duxbury, MA (Richards)  
WOODWARD-CLYDE CONSULTANTS PLYMOUTH MEETING PA (CROSS, III)  
AL SMOOTS Los Angeles, CA  
BRAHTZ La Jolla, CA  
BRYANT ROSE Johnson Div. UOP, Glendora CA  
BULLOCK La Canada  
F. HEUZE Boulder CO  
G.L. KALOUSEK Lakewood Co.  
HAMEED ELNAGGAR Wexford PA  
J.G. KLUBALL Castro Valley CA  
CAPT MURPHY Sunnyvale, CA  
GREG PAGE EUGENE, OR  
R. E. PRICE Dover N.J.  
R.F. BESIER Old Saybrook CT  
R.Q. PALMER Kaitua, HI  
S.T. LI Rapid City, S.D.  
SMITH Gulfport, MS  
T.W. MERMEL Washington DC

END  
1-78  
DDC